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Behavior of pellets combustion produced with pine and RDF (Refused derived fuel) in a domestic boiler.

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A me ed al coraggio. Ai cambiamenti ed alle opportunità.
A Mario,mio fratello,che mi insegna cosa vuol dire lottare.
A mamma, papà e al loro infinito amore.
Alla mia Nonna Rosetta, mia zia Dani e i miei zii Lello ed Ernesto,per l'amore che mi hanno fatto sentire anche quando ero tanto lontana.
A Danilo, il mio amore.

Resumo

O principal objectivo deste trabalho é a avaliação das características físicas e das emissões poluentes decorrentes da combustão de peletes compostas por diferentes tipos de matérias-primas, nomeadamente o *Pinus pinaster* e o combustíveis derivados de resíduos (CDR). O procedimento experimental decorreu Através da utilização de utilização de uma caldeira doméstica (com potência térmica de 20 kW) tendo-se avaliado asua eficiência térmica com a utilização das diferentes misturas do materiais acima referidos.

Os peletes de pinheiro utilizados já estavam certificados de acordo com os padrões ENplus, uma vez que foram cedidos por uma produtora portuguesa. Da mesma empresa também foi cedida a madeira de pinheiro moída utilizada durante a fase de peletização no laboratório dos combustíveis compostos por diferentes percentagens de pinheiro e CDR. Este último foi cedido pelo sistema de gestão de resíduos sólidos urrbanos da Associaçao de Municípios da Região do Planalto Beirão.

Inicilamente começou-se por preparar as misturas dos dois tipos de matérias-primas (pinho e CDR) em três percentagens: 5% de CDR / 95% de pinus, 10% de CDR / 90% de pinus e 15% de CDR / 85% de pinho, avaliando como comparação peletes apenas de pinho. As análises físicas foram então realizadas na matéria-prima (teor de humidade e análise granulométrica). Após o preparação, as características das peletes foram avaliadas (humidade, durabilidade mecânica, teor de finos, tamanho e densidade aparente). Posteriormente, foi avaliada a combustão, nomeadmanete a efeciência da calderia e as emissoes gasosas resultantes do processo, apenas com a carga térmica "alta" na caldeira.

Durante a combustão, a eficiência térmica foi determinada usando o método direto e, em particular, os parâmetros registrados no estado estacionário. No mesmo regime, foram analisadas as emissões poluentes (CO, NO_x e CO_2) e compostos orgânicos voláteis (COV).

Os resultados mostram que a eficiência térmica foi maior no caso de peletes de pinho (cerca de 61%), como esperado, mas foi quase similar no caso dos três tipos de pellets compostos por diferentes percentuais de pinus e CDR (cerca de 50%).

Os níveis de emissões de CO, CO_2 e NO_x, como esperado, são maiores no caso de peletes com CDR em comparação com peletes de pinheiro (100% de pinho). As emissões de CO, em particular, são de cerca de 379 ppm no caso de peletes formados a partir de pinheiro e cerca de 498 ppm e 442 ppm, respectivamente, no caso de peletes formados por 10% e 15% de CDR. A diferença é menos evidente no caso das emissões de CO_2, mas é patente no caso das emissões de NO_x e NO. De facto, para o NO_x existem emissões de cerca de 90, 150 e 164 ppm, respectivamente, para combustíveis formados por pinho, 10% e 15% de RDF. A mesma tendência ocorre no caso das emissões de NO.

Abstact

The main object of this work is the evaluation of the physical characteristics and the pollutant emissions resulting from the combustion of pellets composed of different types of raw material, namely *Pinus pinaster* and refused derived fuel (RDF). The thermal efficiency of the domestic boiler (with a thermal output of 20kW) used in the experiments was also evaluated.

The pine pellets used were already certified according to ENplus standards as they were ceded by a Portuguese manufacturer. From the same company was also ceded the milled pine wood used during the pelletizing phase, performed in the laboratory, of fuels composed of different percentages of pine and RDF. This last one was provided by the Assocaiaçã de Municipios da Região do Planalto Beirão waste management system.

The first step was to mix the two types of raw material (pine and RDF) in three differents percentages: 5% of RDF/95% of pine, 10% of RDF/90% of pine and 15% of RDF/85 % of pine, having 100% pine as reference. Then the physical analyzes on the raw material were performerd (humidity content and particle size distribution). After their pelettization, the characteristics of the experimental pellets were evaluated (humidity content, durability, fine content, dimensions and bulk density).

During the combustion, with the "high" thermal load, the thermal efficiency was determined using the direct method through parameters recorded in the stationary regime. In the same regime the pollutant emissions (CO, NO_x and CO_2) were analysed, as well as the volatile organic compounds (VOCs).

The results show that the thermal efficiency was higher in the case of pine pellets (about 61%), as expected, but it was almost similar in the cases of the three types of pellets composed of different percentages of pine and RDF (approx. 50%).

The levels of CO, CO_2 and NO_x emissions, as expected, are higher in the case of pellets also formed by RDF compared to pine. The CO emissions in particular are about 379 ppm in the case of pellets formed from pine and about 498 ppm and 442 ppm respectively in the case of pellets formed by 10% and 15% of RDF. The difference is less evident in the case of CO_2 emissions but very evident in the case of NO_x and NO emissions. In fact, for NO_x there are emissions of about 90, 150 and 164 ppm respectively for fuels formed by pine, 10% and 15% of RDF. The same tendency will occur in the case of the NO emissions.

Astratto

Lo scopo principale di questo lavoro è la valutazione delle caratteristiche fisiche e delle emissioni inquinanti derivanti dalla combustione di pellet composti da diversi tipi di materie prime, vale a dire Pinus pinaster e combustibile solido secondario (CSS). È stata anche valutata l'efficienza termica della caldaia domestica (con una potenza termica di 20 kW) utilizzata negli esperimenti.

I pellet di pino usati erano già certificati secondo gli standard ENplus in quanto ceduti da un produttore portoghese. Dalla stessa azienda è stato anche ceduto il legno di pino macinato utilizzato durante la fase di pellettizzazione, eseguita in laboratorio, di combustibili composti da diverse percentuali di pino e CSS. Quest'ultimo è stato fornito dal sistema di gestione dei rifiuti di Associazione di comuni della regioni di Planalto Beirão.

Il primo passo consisteva nel mescolare i due tipi di materie prime (pino e CSS) in tre percentuali diverse: 5% di CSS / 95% di pino, 10% di CSS / 90% di pino e 15% di CSS / 85% di pino, con pino al 100% come riferimento. Poi sono state eseguite le analisi fisiche sulla materia prima (contenuto di umidità e distribuzione delle dimensioni delle particelle). Dopo la loro pelettizzazione, sono state valutate le caratteristiche del pellet sperimentale (contenuto di umidità, durata, contenuto fine, dimensioni e densità apparente).

Durante la combustione, con il carico termico "alto", l'efficienza termica è stata determinata utilizzando il metodo diretto attraverso i parametri registrati nel regime stazionario. Nello stesso regime sono state analizzate le emissioni inquinanti (CO, NO_x e CO_2), nonché i composti organici volatili (COVs).

I risultati mostrano che l'efficienza termica era maggiore nel caso di pellet di pino (circa il 61%), come previsto, ma era quasi simile nei casi dei tre tipi di pellet composti da diverse percentuali di pino e CSS (circa 50 %).

I livelli di emissioni di CO, CO_2 e NO_x, come previsto, sono più alti nel caso di pellet formato anche da CSS rispetto al pino. Le emissioni di CO in particolare sono circa 379 ppm nel caso di granuli formati da pino e circa 498 ppm e 442 ppm rispettivamente nel caso di pellet formato dal 10% e dal 15% di CSS. La differenza è meno evidente nel caso delle emissioni di CO_2, ma molto evidente nel caso delle emissioni di NO_x e NO. Infatti, per NO_x ci sono emissioni di circa 90, 150 e 164 ppm rispettivamente per i combustibili formati da pino, il 10% e il 15% di CSS. La stessa tendenza si verificherà nel caso del NO inquinante.

Palavras-chave: combustão, pellet, CDR (combustível derivado recusado),pinho,caldeira doméstica, biomassa.

Keywords: combustion, pellet, RDF (Refused derived fuel), pine, domestic boiler, biomass.

Parole chiave: combustion, pellet, CSS (Combustibile solido secondario), pino, caldaia domestica, biomassa.

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ABREVIATIONS

CDR	Combustíveis derivados de resíduos
CEN	European committee for standardization
COV	Compostos orgânicos voláteis
COV	Composti organici volatili
CSS	Combustibile solido secondario
EC	European comission
EEA	European Union Environment Agency
EU	European Union
HHV	Higher heating value,(kg/kJ)
ISO	International organization for standardization
LHV	Lower heating value,(kg/kJ)
MBT	Mechanical and biological treatments
MSW	Municipal solid urban waste
RDF	Refused derived fuel
SRF	Solid recovered fuel
VOCs	Volatile organic compounds

SYMBOLS

$\dot{m}_{H2O}$	Mass flow rate of water,(kg/s)
$\dot{m}_{pellet}$	Pellet mass flow rate,(kg/s)
cp_{H2O}	Specific heat of the water,[kJ/(kg °C)]
$mass_{pellet}$	Mass of the pellet (g);
PCI_{pellet}	Lower heating value (LHV) of the pellets,(kJ/kg)
$Volume_{pellet}$	Volume of the pellet,(m^3)
ρ_{pellet}	Particle density,(kg/m^3)
ΔT	Difference between the average entering and leaving water temperatures,(°C)
BD	Bulk density,(kg/m^3)
D	Pellet diameter,(mm)
d_p	Particle diameter, (mm)
d_{pi}	Arithmetic spacing average of the sieves of two subsequent sieves,(mm)
DU	Mechanical durability,(%)
F	Amount of fine material,(%)
h	Pellet length,(mm)
H_{bs}	Dry basis humidity,(%)
H_{bu}	Wet basis humidity,(%)
m_1	Mass of the empty container,(kg)
m_2	Mass of the full container,(kg)
m_A	Mass of sieved particles,(g)

SYMBOLS

m_d	Dry mass of the material,(g)
m_E	Mass of the sample before sieving,(g)
m_w	Wet mass of material,(g)
V	Net volume of the measuring cylinder,(m^3)
x_i	Mass fraction of the particles of material retained in the interval i,(-)
η_T	Thermal efficiency,(%)
$H\ (bs)$	Hydrogen contained in the material in dry base,(%)

1. Introduction

The final disposal of municipal solid urban waste (MSW) is still a problem in many countries, including European countries.

The increase in the price of raw materials, the lack of space for new landfills, the problems deriving from leachate and the restrictions imposed by European regulations have led to the idea of being able to use waste-derived fuels and biomass to replace fossil fuels. To do this it need an increase in the correct collection of materials and therefore of energy that lead to a lower environmental impact, lower consumption of energy resources and lower economic costs.

A system that aims good waste management pratices promotes the reduction of greenhouse gases and reduces the volumes of waste destined for landfill (Menikpura, 2013).

Another alternative to landfills is waste heat treatments and in particular refuse derived fules (RDFs) that reduce volumes, therefore spaces and through which energy is recovered (Gallardo et al., 2014). In any case, it is essential to make the correct estimate of the possible energy content of the residual fraction of the mechanical and biological treatments (MBT) and therefore of the RDF, for the planning of energy production through its combustion (Aranda et al., 2012).

The study of biomass, and therefore its quality, is essential if it is to be used for energy purposes. The energy production referred to is carried out in small domestic appliances although they do not have a high quality. All this greatly limits their use but, they have achieved good results in terms of thermal efficiency. Many studies have been carried out on the combustion of biomass and its combustion with other types of fuels and the current trend is to focus on the analysis of its characteristics especially in terms of emissions (Arranz ,?).

Biomass pellets currently play a large role in heat and energy production and the pellet market is in a phase of rapid development. In fact, it is estimated that in the future it may be one of the major sources of energy production but this leads to the realization of a good production chain. This will also be useful to make this type of fuel competitive compared to others that are generally predominant on the market (Selkimäki et al., 2010).

The objective of this work is to analyze the physical and combustion properties of commercial pine pellets and laboratory-produced pellets by combining biomass (pine wood) and RDF. The aim of the work is to be able to lay the foundations for more in-depth studies on the use of RDF for energy production.

The experimentation was conducted with the use of a domestic boiler (20kW) and all the necessary data were analysed in order to understand the combustion, although the main goal is not aimed at the use of biomass pellets (pine wood) and waste for domestic use, but rather for energy production through the combustion of large quantities of fuel in industries. This would lead, as already mentioned, to the reduction of large quantities of waste destined for landfills and therefore to their transformation into something useful and productive.

It should be noted that it would be utopian, at least in our day, to consider using waste combustion in homes because, given their composition, it is easy to think that they have different gas emissions and may be harmful to human health.

1.1. Work objective and procedure

The main objective of this work is the evaluation of energy parameters resulting from combustion of RDF pellets and biomass pellets in a domestic boiler (nominal power of 20 kW). The aim is to demonstrate, in terms of emissions, pellet's characteristics and energy production, that their use is alternative to fossil fuels. This will eliminate the use of coal or other fossil fuels in thermoelectric power plants and therefore will lead to savings in economic and environmental terms as well as reduce the amount of landfilled waste.

In particular, the intention is to compare the results obtained with the use of pellets made of RDF and pine tree wood, with pellets composed of pine alone (certified according to ENplus standards).

The main process on which the following work focuses is the combustion of pellets composed of RDF and biomass. In particular, the procedure can be described in four basic steps:

1) **Milling process** which consists of reducing the raw material into smaller pieces;
2) **Pelletizing materials** (RDF + pine), mix pine and RDF in a pelletizing equipment to compact the material and give it the shape of the pellets in order to achieve a biomass densification (according to EN 14780 - Sample preparation). Pellets with different percentages of materials were done and tests were carried out:
    - 5% RDF + 95% pine,
    - 10% RDF + 90% pine,
    - 15% RDF + 85% pine;
3) **Physical characterization of pellets** evaluating the humidity, durability, content of fine particles, diameter, length and apparent density (the properties will then be compared and verified based on the normal ENPlus EN 14961-2);
4) **Pellet combustion** in a domestic stove (20 kW) using only the "high" thermal load and the simultaneous evaluation of combustion efficiency and gas emissions.

1.2. Work organization

The work is mainly divided into 5 chapters which outline the organization and timing of the work itself.

The first section focuses on the general problem of waste and on Europe's future objectives regarding this topic. Furthermore, the focus is on the identity of the pellets and the potential that the mixing between wood pellets and waste can have. No less important in this section is the issue of emissions that when it comes to combustion, is always in the foreground.

The second part of this study deals with is the description of how the experimental work was carried out with reference to the standards. The latter are also taken into consideration in the chapter "Results and discussion" in which the values obtained from the experimental work are set out with reference to other studies.

The fifth part is almost the summary of what ended at the end of the research. In addition to the conclusion, suggestions for future work are added.

1.3. Work schedule

Table 1: Time schedule of the work carried out over the five months.

Task	March 2019	April 2019	May 2019	June 2019	July 2019
T1	■	■			
T2	■	■			
T3		■	■		
T4			■	■	
T5			■	■	■

Table 2: Description of the sections of the work carried out over the five months.

Task	Title	Description
T1	Literature review	Collection of information on the effects of combustion of refuse derived fuels RDF (with biomass and the impact on energy and gas emissions.
T2	Preparation of combustible mixes	Preparation of mixes for combustion in a domestic boiler - evaluation of technical difficulties and best practice.
T3	Burning assays with evaluation of thermal efficiency and gaseous emissions	Burning tests of the prepared mixes and data collection.
T4	Data analysis	Data analysis and statistical evaluation.
T5	Thesis	Thesis organization and work presentation.

INTRODUCTION

2. Literature Review

2.1. Fossil fuels and biomass

One of the most widely used fossil fuels in the world today is coal despite strong competition in the market with other types of fuels and despite their negative environmental impact. In fact, it is the most popular source of energy production due to its abundance and because over the years many different technologies have been developed for the advanced coal combustion for energy production. Generally the greater use of coal is in the field of electricity production (Demirbas,2003).

When it comes to fossil fuels it is may find "non-renewable" and in fact these energy sources are destined to run out very soon. These hydrocarbons also represent the main source of greenhouse gases, responsible for important environmental phenomena such as the greenhouse effect, acidic rain and global warming. When they are burned to produce energy, they release large amounts of CO_2 and pollutants that create a great impact on the environment. Unfortunately, their use has much lower cost than renewable energy sources and can release greater amounts of energy. Hydrocarbons such as oil, methane and coal owe their fortune to these factors, the ease of their transport and political and multinational interests.

Biomass fuels, a renewable source of energy, are growing strongly. Biomasses are all the products of agricultural and forestation, agricultural processing residues and food industry waste, algae, all organic products deriving from animal biological activity.

The combustion of biomass allows an energy recovery through, for example, thermochemical treatments. They are based on the exothermic reactions of biomass combustion (for example wood and its derivatives). Their main use is heat production. In fact, even if very often it is not realized, it is used biomass to heat our homes (fireplaces, pellet stoves, etc.) and sometimes even to cook (using charcoals and wood stoves).

The second use of biomasses, even if not direct, is the conversion of the heat produced by their combustion to produce electricity. This can be done in traditional plants that use gas, coal, etc. or by replacing it with biomass.

The use of fuel biomass could lower the level of environmental alert because it contains a low level of nitrogen and ash. Furthermore, biomass is considered a "CO_2 neutral fuel" because it consumes the same amount of CO_2 that it emits during combustion. This implies that there is a balance between what is emitted and what is absorbed and does not contribute to the greenhouse effect (Demirbas, 2003; Klason and Bai, 2007).

2.2. What are RDFs

RDFs are fuels derived from the last treatment phase of solid waste, or the so-called "rejected". This type of fuel is the product of the last phase of the Mechanical and Biological Treatment (MBT) process. It is aimed at stabilizing the organic fraction present in the residual undifferentiated waste and at the possible enhancement of the fraction with high heating value through the production of RDF.

The phases of the urban waste treatment process is shown in the Image 1, are: separation of the waste at the origin, sorting or mechanical separation, reduction of the dimensions (shredding, cutting and milling), separation and screening, mixing, drying and pelletisation.

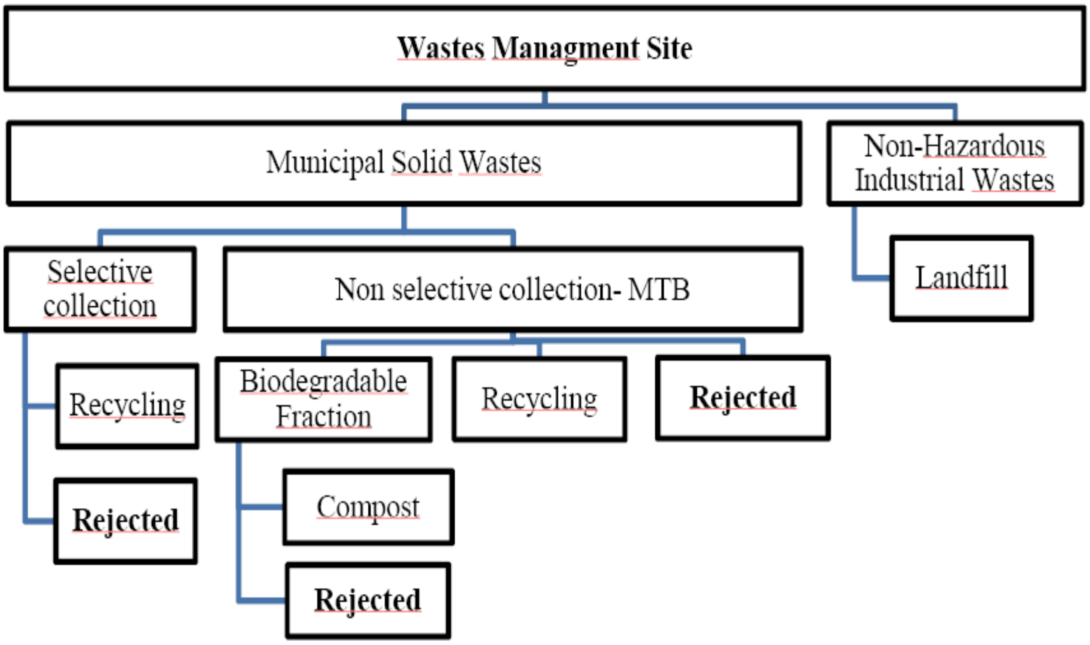


Image 1: Waste treatment cycle (Adapted from Brás et al, 2017).

Municipal solid waste (MSW) is first treated and passed through a magnetic separator. It is then sent to a ballistic separator to separate the low heating waste. The rest of the waste material is filtered to remove the recyclable fractions (eg metals), the inert fractions (for example glass) and the wet fraction (for example food) before the material is pulverized. In this way, the fuel produced from the waste is called RDF which are then sent to the RDF storage area.

The heating value of the RDFs, based as they are, is around 4000 kcal/kg and the reason for such a high heating value is the presence of plastic, paper or cardboard in RDF. RDFs also contain a high biomass value and this depends on the nature of urban waste and the organic or fuel content that is also related to the standard of living and consumption habits of the place where it is produced (Brás, 2017; Kara, 2012).

As a result of the treatment of MSW in an MBT plant, paper and cardboard, cardboard, metal, plastic, glass packaging and organic waste are separated from the residual fraction which cannot be exploited and this is finally discharged into a landfill. But this residual fraction, also called waste fraction, can be profitable from the environmental and economic point of view. It can be turned into waste-derived fuel (RDF), which is waste that has been treated (or processed). This process consists in eliminating the non-combustible fraction, reducing the size and moisture content, homogenizing the waste, and in some cases its transformation into granules and pellets (Gallardo, 2014).

It should be specified that the waste that can be used can be RDF and solid recovered fuel (SRF) that have a small but important difference. It consists in quality: by appropriately treating the RDF (removal of materials that have lower heating value) it is possible to derive the SRF. The bacterial load is eliminated, the humidity is reduced up to a maximum of 5% and regular shapes are made in order to compact the material into pellets. This obviously implies a greater investment in energy and resources, which is why it is often considered almost indifferent to use RDF rather than SRF.

2.3. Objectives of Europe

Although the combustion of RDF and biomass pellets is very advantageous, there are also many concerns related to emissions of dust, NO_x, SO_x into the environment. Precisely for this reason, each country and each installation must comply with European standards.

For many years, research in the European Union (EU) has been conducted with the aim of finding a useful, economical and environmentally compatible way to reuse waste for energy production. Currently it is produced using fossil fuels which, however, have less stable chemical-physical characteristics than fuels derived from waste (RDF), which currently represent an alternative source of fuel.

Over the years there has been a fat and continuous increase in the production of waste that stopped at the beginning of the economic crisis. This led to a decrease in consumption which in turn led to a reduction in waste production. Despite this, the value recorded in 2012 for the production of urban waste per capita was 247 million tons in Europe (Massarini and Muraro,2015).

In 2014, Austria, Belgium, Denmark, Germany, the Netherlands and Sweden sent virtually no urban waste to landfills, while Cyprus, Croatia, Greece, Latvia and Malta still dispose of more than three quarters of their urban waste in landfills.

Although waste management in the EU has significantly improved in recent decades, almost a third of municipal waste is deposited in confined spaces and less than half is recycled or composted (with wide variations between Member States).

In 2020, every citizen will produce 558 kg of waste. The forecast was launched by the European Union Environment Agency not without fear. From the studies carried out, it was possible to realise that every year in Europe the quantity of waste produced by every single inhabitant grows: if in 1995 the annual garbage per capita was about 468 kg, in 2008 it rose to 524 and in 2020 it will be 558 kg if not action is taken (EEA, 2011).

Looking at the image 2 it is possible to observe the growth of waste production in the last few years and the average production in terms of kg per person.

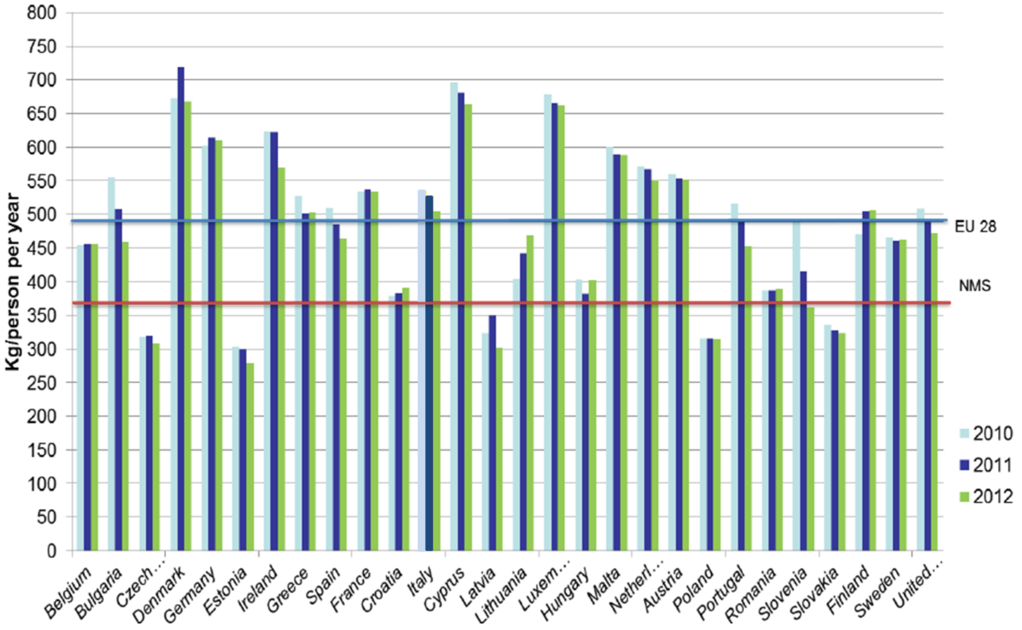


Image 2: Production of Waste in EU year 2012 (kg/person) (Massarini and Muraro,2015).

The damage resides in the environment, for example with the release of leachate, but also in the amount of CO and equivalent emissions produced in landfills. An excellent start is to limit the waste that ends up in landfills, recycling all the materials that can be used again for the production of new materials.

Improving waste management could provide benefits for the environment, climate, human health and the economy. As part of a change in EU policy towards a circular economy, the European Commission has made four legislative proposals that introduce new targets in waste management with regard to re-use, recycling and landfill disposal.

Currently the objective of Europe with respect to the problem is to reach a recycling rate of 65% of urban waste and 80% of packaging by 2030 (EC, 2015; EU, 2018)

The objective has therefore been shifted, from recycling up to 50% of urban waste in 2020, to the new and more ambitious goal of 2030.

The proposed measures, which would also make it possible to reduce the environmental impact and emissions of greenhouse gases, provide for the prohibition from 2025 of placing recyclable waste in landfills.

Innovative design, better and more resistant products, more efficient and sustainable production processes, far-sighted business models and technical advances to transform waste into a resource will contribute to increasing efficiency.

2.4. Pellets and their development

History tells us that wood has always been the most used method to produce thermal energy. This condition remained until the 1920s after the fossil fuels took over which, however, are known to involve a high rate of pollution.

The alternative today is wood pellets which have become an important fuel in terms of heat production. The reason for their development is the size of the cylinders, ease of transport and emissions.

The production of pellets takes place in a pelletizing equipment sometimes with the addition of binders that facilitate compaction. These fuels are cylindrical in shape, usually with a low moisture content and high heating value. Another advantage of the use of fuels that possess this regular geometry is the feeding phase. In fact, the pellet stove has a screw that supplies the combustion chamber at constant time intervals. If the pellets did not have this shape the mechanism would probably be blocked. They even have CO_2 emissions close to defining them as "neutral", a great potential from the point of view of energy and they are easy to transport abroad (Sikanen,2008; Selkimäki, 2010).

The popularity of pellets is extended in many countries of the world and especially throughout Europe where it is still evolving. The increase in the number of domestic systems installed (pellet stoves) has allowed a development of the market of this type of fuel to satisfy the continuously growing demand. This type of equipment as reported in other studies are very competitive with those in oil or gas in terms of energy but above all in terms of maintenance (Selkimäki, 2010).

The wood pellet market, in fact, has grown internationally (Junginger et al., 2008) with a size that has even doubled from 2007 to 2010 (Savolainien, 2007). The market capacity has increased more rapidly than expected, with an approximate production of 6.2 million metric tons (Spelter and Toth 2009; Mani 2006).

There is a need to ensure good quality throughout the chain (production, delivery and storage) to support the further development of this type of fuel and make it competitive with fossil fuels (Selkima¨ki, 2010). The producers of densified biomass fuels, and specifically the producers of pellets, are obliged to guarantee the high quality of the product to remain within the limit values required by the regulations.

The leader producers of pellets are Germany, Sweden, Latvia, Estonia and France while the consumers are the United Kingdom followed by Denmark and Italy (Bioenergy Europe, 2019). Among the major producers of pellets there is also Portugal followed. The pellet market in Portugal since 2005 has undergone a strong development mainly for domestic use, public buildings and small industries. Not all biomass fuels produced in Portugal are destined for internal consumption. In fact, most of them (90%) are exported to northem Europe (Ferreira,2013).

The results of some research (Obernberger and Thek,2004) also show that pellets from Austria, Italy, Sweden, Spain, Norway and the Czech Republic are of very good quality.

In general it can be said that the market for this type of fuel in the last 10 years has undergone a strong global growth (average increase of around 14% since 2011). New countries have been involved in production and consumption like East Asia. To date, the leaders in the intercontinental trade sector are still the United States and the United Kingdom. This excludes that for the sale of pellets for domestic use the activity is intra-European (Thrän et al. 2017).

Image 3 shows the world situation of the pellet market.

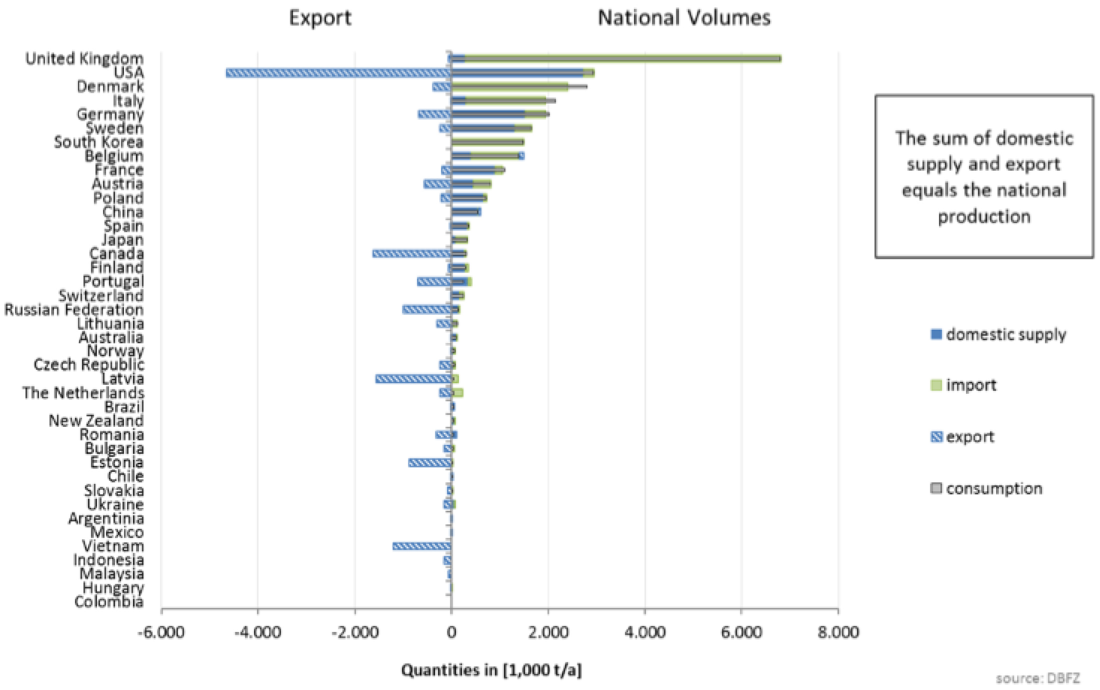


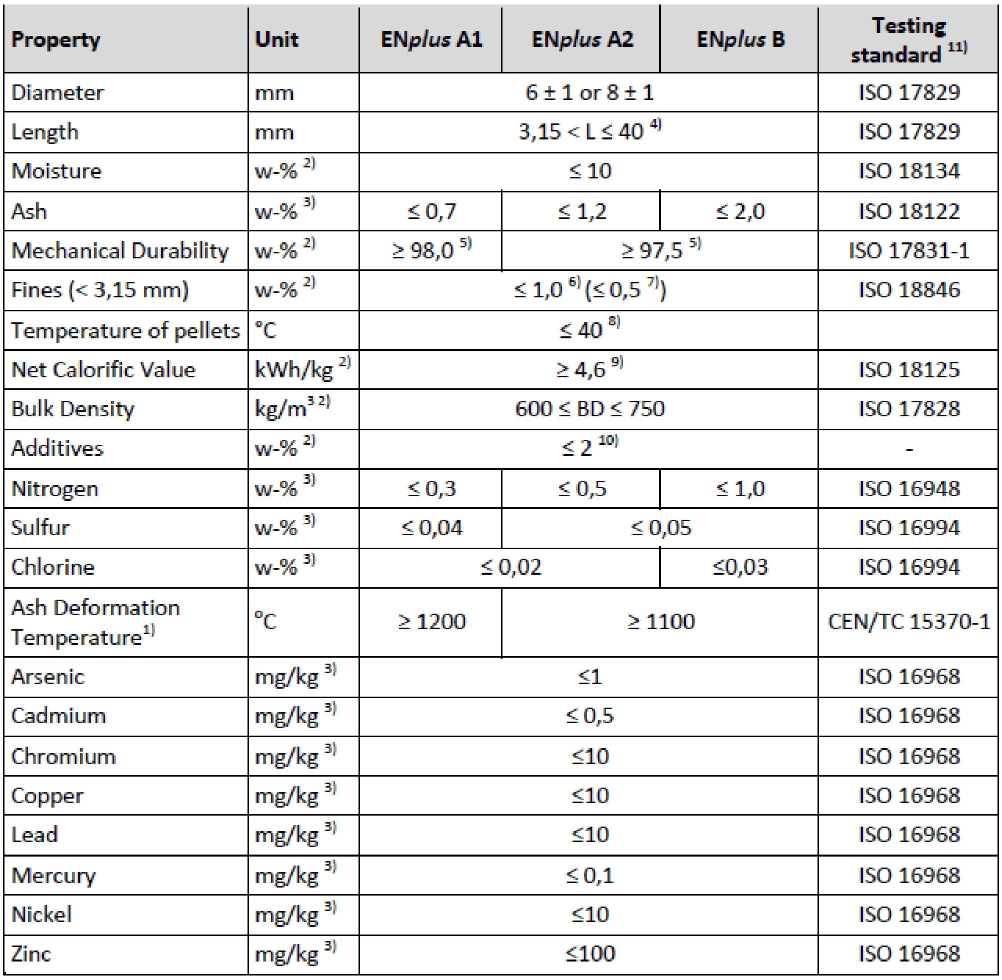
Image 3: Domestic Production and Import | Export per country for chosen countries in 2015/2016; sorted by consumption (Thrän et al. 2017).

To date, the goal is to promote the use of these materials for small and large consumers in order to standardize their production and stabilize their prices. In the near future therefore the aim is to increase the possibilities of its expansion and the development of new raw materials for their production. Furthermore, it is necessary to build trust in buyers who, as with everything new, do not place much trust in this technology.

2.5. ENplus Normative

The certified pellets present on the European market can have different acronyms and among these, one of the most widespread and known is the ENplus Certification.

In 2011 the ENplus certification system was born, thanks to a tight agreement within the European Pellet Council, with the aim of certifying pellets as fuels and guaranteeing a high quality of combustion. ENplus is an additional element that allows the consumer to rely on the brand and choosing an efficient product.The European technical reference standard is EN 14961.



<table>
<tr><th>Property</th><th>Unit</th><th>ENplus A1</th><th>ENplus A2</th><th>ENplus B</th><th>Testing standard 11)</th></tr>
<tr><td>Diameter</td><td>mm</td><td colspan="3">6 ± 1 or 8 ± 1</td><td>ISO 17829</td></tr>
<tr><td>Length</td><td>mm</td><td colspan="3">3,15 < L ≤ 40 4)</td><td>ISO 17829</td></tr>
<tr><td>Moisture</td><td>w-% 2)</td><td colspan="3">≤ 10</td><td>ISO 18134</td></tr>
<tr><td>Ash</td><td>w-% 3)</td><td>≤ 0,7</td><td>≤ 1,2</td><td>≤ 2,0</td><td>ISO 18122</td></tr>
<tr><td>Mechanical Durability</td><td>w-% 2)</td><td>≥ 98,0 5)</td><td colspan="2">≥ 97,5 5)</td><td>ISO 17831-1</td></tr>
<tr><td>Fines (< 3,15 mm)</td><td>w-% 2)</td><td colspan="3">≤ 1,0 6) (≤ 0,5 7))</td><td>ISO 18846</td></tr>
<tr><td>Temperature of pellets</td><td>°C</td><td colspan="3">≤ 40 8)</td><td></td></tr>
<tr><td>Net Calorific Value</td><td>kWh/kg 2)</td><td colspan="3">≥ 4,6 9)</td><td>ISO 18125</td></tr>
<tr><td>Bulk Density</td><td>kg/m3 2)</td><td colspan="3">600 ≤ BD ≤ 750</td><td>ISO 17828</td></tr>
<tr><td>Additives</td><td>w-% 2)</td><td colspan="3">≤ 2 10)</td><td>-</td></tr>
<tr><td>Nitrogen</td><td>w-% 3)</td><td>≤ 0,3</td><td>≤ 0,5</td><td>≤ 1,0</td><td>ISO 16948</td></tr>
<tr><td>Sulfur</td><td>w-% 3)</td><td>≤ 0,04</td><td colspan="2">≤ 0,05</td><td>ISO 16994</td></tr>
<tr><td>Chlorine</td><td>w-% 3)</td><td colspan="2">≤ 0,02</td><td>≤0,03</td><td>ISO 16994</td></tr>
<tr><td>Ash Deformation Temperature1)</td><td>°C</td><td>≥ 1200</td><td colspan="2">≥ 1100</td><td>CEN/TC 15370-1</td></tr>
<tr><td>Arsenic</td><td>mg/kg 3)</td><td colspan="3">≤1</td><td>ISO 16968</td></tr>
<tr><td>Cadmium</td><td>mg/kg 3)</td><td colspan="3">≤ 0,5</td><td>ISO 16968</td></tr>
<tr><td>Chromium</td><td>mg/kg 3)</td><td colspan="3">≤10</td><td>ISO 16968</td></tr>
<tr><td>Copper</td><td>mg/kg 3)</td><td colspan="3">≤10</td><td>ISO 16968</td></tr>
<tr><td>Lead</td><td>mg/kg 3)</td><td colspan="3">≤10</td><td>ISO 16968</td></tr>
<tr><td>Mercury</td><td>mg/kg 3)</td><td colspan="3">≤ 0,1</td><td>ISO 16968</td></tr>
<tr><td>Nickel</td><td>mg/kg 3)</td><td colspan="3">≤10</td><td>ISO 16968</td></tr>
<tr><td>Zinc</td><td>mg/kg 3)</td><td colspan="3">≤100</td><td>ISO 16968</td></tr>
</table>

Image 4: Threshold values of the most important pellet parameters (Adapted from ENplus 14961-2).

This particular certification includes checks not only in the selection of the raw material, but also in the procedures followed within the production plant. Within the ENplus certification scheme, three different classes of pellet quality are defined:

- ENplus A1;
- ENplus A2;
- ENplus B.

Each class is determined by the technical characteristics of the product and the raw material used. The highest quality class is ENplus A1. In Image 4, the difference in the parameters between the various classes are shown.

The additives allowed in the ENplus certification are only biological products and in a maximum quantity equal to 2% of the total weight of the pellet. The type and quantity of all the additives used must be carefully documented.

The substances allowed, as mentioned, are exclusively natural, like starch, masi flour, potatoes or vegetable oil. Generally, they are added to increase the quality of the fuel.

However, the low percentage of these elements that is inserted guarantees the need to select raw materials which, alone, already guarantee high results.

ENplus not only guarantees a high level of fuel yield but, thanks to the activation of a monitoring system entrusted to a third body, it is able to attest to the safety and sustainability of the production process.

2.6. Combustion

Combustion is a highly exothermic chemical oxidation phenomenon that occurs between a fuel and oxygen with an intense light manifestation and heat emission. The essential conditions for combustion to occur are (Image 5):

- Having a fuel;
- Having air, to have oxygen;
- Having a particular ignition or temperature called flammability temperature.

Most combustion reactions concern the rapid oxidation of the substance by O_2, but reactions that occur even in the absence of O_2 are known. In reality it is more opportune to speak of an oxide-reduction reaction rather than a simple "oxidation". In these reactions the oxidizing species is called comburent and the reducing species is called fuel (Anticendio Italia,2017).

A combustion that has a high thermal efficiency involves the emission of less harmful products. Wanting to refer to fossil fuels, what happens during the oxidation-reduction reaction is the transformation of hydrogen into water and carbon into carbon dioxide (as can be seen from the equation below). It may happen that the carbon is oxidized to an intermediate level of reaction and in that case the formation of carbon monoxide (CO) occurs (as shown in the equation below). If the combustion reaction will take place completely, the formation of carbon dioxide (CO_2) will occur (as shown in the equation below).

$$\mathrm{H_2} + \frac{1}{2}\mathrm{O_2} \rightarrow \mathrm{H_2O} + \ 241{,}8\ \mathrm{kJ/mol}$$

$$\mathrm{C} + \mathrm{O_2} \rightarrow \mathrm{CO_2} + \ 383{,}5\ \mathrm{kJ/mol}$$

$$2\mathrm{C} + \mathrm{O_2} \rightarrow 2\mathrm{CO}$$

CO is a highly toxic product whose formation involves an energy loss as well as an objective risk for human health. Another risk factor and a reduction in energy efficiency lies in the incomplete oxidation reaction of the hydrocarbons, leading to the VOCs formation. The latter is also influenced by the combustion speed which, as in many other types of reactions, increases with increasing temperature. When the temperature is low (<1000°C) the combustion takes place slowly with energy dissipation (slow combustion). In this case there is a branched chain mechanism with the formation of more or less stable intermediates with significant life times. These intermediates, for example, are the cause in the combustion of hydrocarbons from the formation of VOCs between products (Cavaliere,2017;Anticendio Italia,2017).

2.6.1. Stationary regime

From an engineering point of view, the essential problem, in the presence of heat transmission, is the determination of the thermal power transmitted for a given temperature difference (ΔT). The size of the boilers, for example, or heat exchangers in general, in fact, does not depend only on the amount of heat exchanged but also on the thermal power. This makes us understand that time is a fundamental variable for the study of heat transmission (Gómez and Watterson,2006).

In the present work the temperature reached is studied during the combustion of a certain mass of pellets made available for the stove. In particular, is studied the variation of the temperature of the combustion gases over time and therefore during the transitory regime phase and then during the stationary regime phase. The transitory regime includes that period in which, following the ignition, the temperature increases, the flame expands and involves all the fuel.

Most interesting for research and for determining thermal efficiency are the values studied in the stationary regime phase. The reason lies in the definition of a stationary regime which is the phase of combustion (before switching off) during which a certain temperature is reached which remains unchanged over time. It is clear that in this way, having a constant factor, it will be easier and more correct to study all the other combustion characteristics (Gómez and Watterson,2006).

2.6.2. Biomass combustion

Good combustion involving biomass must have low emissions and a low residue content which requires a good supply of air, good mixing of fuel (pellets)/oxidising (air) and the right mass supply inside the equipment. The latter must be divided into a primary and a secondary combustion zone and each of them must have its own air supply.

Usually the combustion is made by about primary and secondary air, which intervene in the process in two successive steps. The primary air is allowed to enter the combustion chamber of the biomass boiler (in a natural way or with forced ventilation) in the area of the grid, to allow the ignition of the wood material (the start of combustion). This phase, for biomasses, is called gasification. Combustible gases are developed such as hydrogen and carbon monoxide, which, when properly conveyed to the brazier area, help combustion thanks to the introduction of secondary air (also introduced near the embers) with the aim of maximizing the combustion of the biomass.

In the primary combustion zone there will be a second phase during which the gases produced by the first phase are burned in the presence of excess air. It is necessary that there is a good mix between the gases produced in the first phase and the air supplied during the second. The longer the gas stays in the boiler, the better the combustion will be. The supply of primary air and secondary air can be seen in Image 5.

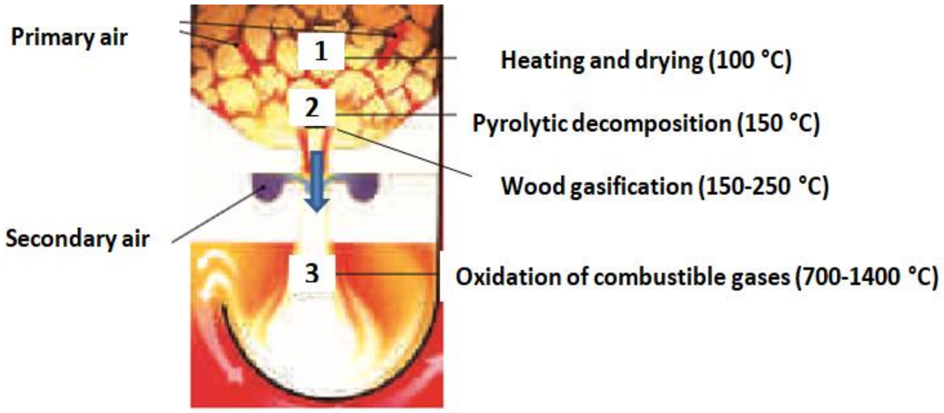


Image 5: Stages of combustion in a forced draft suction stove (primary air and secondary air) (primary air and secondary air) (Francescato et al.,?).

The stages into which the biomass combustion process is divided are shown in the Image 6.

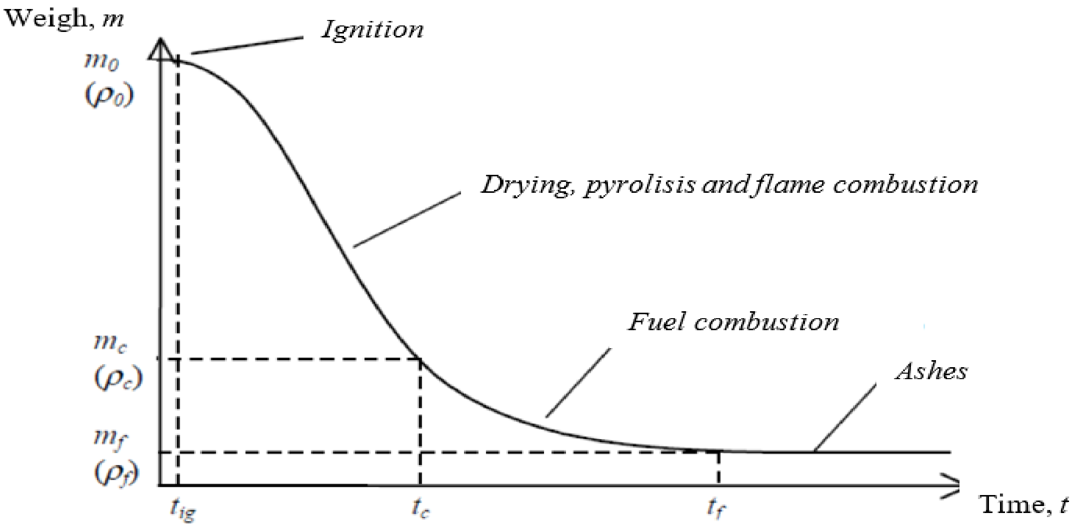


Image 6: Evolution of the mass of a biomass particle during the combustion process (Dias, 2002).

The combustion stages may be described as:

- The ignition that provides thermal energy to the fuel. It follows its heating through the irradiation of the flame in most of the combustion chamber;

- The drying of the fuel through the heat generated in the previous phase and the consequent evaporation of the water (the combustion temperature is around 100 ° C);
- the pyrolysis that involves the decomposition of the fuel (the boiler temperature is around 150 ° C);
- The gasification of the substance that is now dried (the combustion temperature is around 250°C). In this phase the formation of combustion gases and solid coal occurs;
- Gasification of solid coal with consequent formation of CO and CO_2, water vapor and release of O_2 (the combustion temperature is around 500°C);
- Final reaction of the fuel reaching temperatures in a range of 700-1400°C and oxidation of combustible gases.

The flame will thus expand to the new fuel supplied by the boiler hopper (Francescato and Antonini,2009).

2.6.3. Gaseous emissions

The formation of polluting emissions depends mainly on the quality and completeness of the combustion. In particular from the combustion temperature, from the quality of the mixing between fuel and air supplied and the too short time of permanence of the combustible gases in the combustion area. The "not-burned" pollutants are CO, HC, tar, polycyclic aromatic hydrocarbons (PAH), hydrocarbons (C_xH_y) and coal particles while the second category includes ash, nitrogen and sulfur. In particular, the second type of pollutants are closely related to the characteristics of the burned biomass and can include particulate (PM), nitrogen oxides (NO_x, mainly NO and NO_2 and N_2O) and sulfur oxides (SO_x, mainly as SO_2) (Khan, 2009).

2.6.3.1. CO and CO_2 emissions

The main reasons for the formation of CO and CO_2 are linked to the completeness of the combustion. The more complete the combustion, the more CO_2 emissions will be at the expense of CO emissions.

To fully understand the mechanism of formation of these pollutants during thermal processes requires that their combustion chemistry be known as shown in chapter 8.3.4.1 of this work.

It can be said that what is produced during the ideal oxidation reaction (during complete and good quality combustion) is CO_2 and water. In the event that the air supplied to the reaction is insufficient in the combustion zone there will also be the formation of carbon monoxide (CO) (Wielgosiński and Grzegorz,2011).

2.6.3.2. NO_x emissions

Nitrogen compounds include nitrogen oxide (NO) and nitrogen dioxide (NO_2), which are commonly called nitrogen oxides (NO_x) and nitrous oxide (N_2O). All of them play an important role in atmospheric reactions that create a lot of environmental damage like the release of particulate matter in the atmosphere, ozone (smog in general) or acid rain (Khan et al., 2009).

Organic compounds containing nitrogen, such as those found in fossil fuels, participate in the formation of NO_x during combustion. It depends on the amount of nitrogen contained and its concentration in fuels, liquid or solid. Usually in fossil fuels the amount is 0.3-2% nitrogen by weight (Fluent Inc., 2003).

In literature there are many studies on NO_x emissions which suggest that most of them come from fuel nitrogen. Furthermore, it was noted that the formation of nitrogen oxides is decidedly greater when it comes to solid fuels and waste. It is believed that in the case of biofuels, nitrogen is almost entirely in a volatile phase (66-75%) during the devolatilization phase and this occurs when there is a low carbon content. NO_x is formed according to two different and competitive paths, namely the oxidation of the nitrogenous group in the volatile gas phase and through the oxidation of the nitrogenous species linked to coal (Khan et al., 2009).

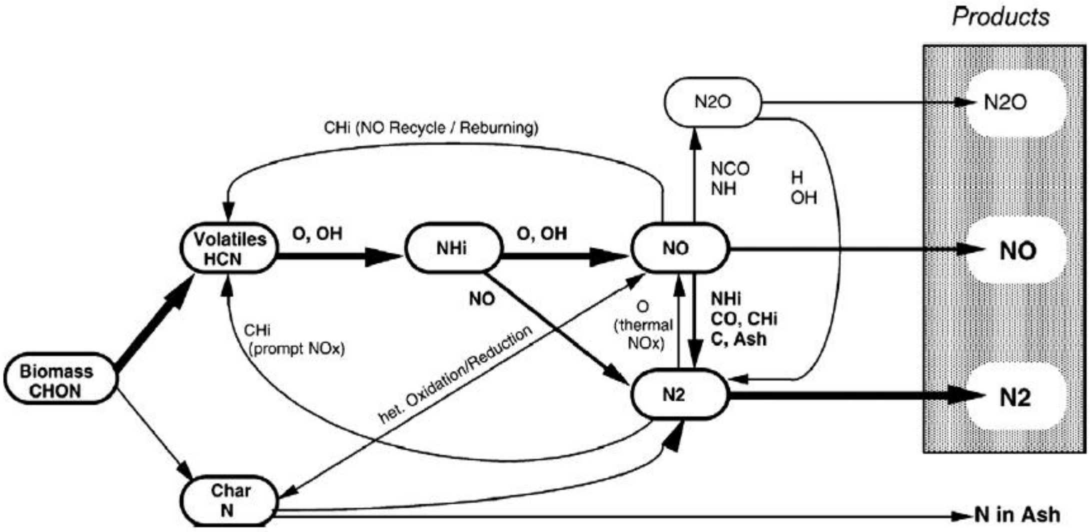


Image 7: Conversion of fuel nitrogen in the case of biomass combustion (Khan et al., 2009).

During combustion, the NO_x are released in the form of particles or droplets during the devolatilization phase of the fuel and the combustion of the coal, following three types of mechanisms during combustion (Williams et al., 2012):

- Thermal NO_x: which are formed under high temperature conditions and in the presence of excess air;
- Fuel NO_x: which are formed from the nitrogen coming from the chemical structure of the fuel;
- Prompt NO_x: they depend on the stoichiometry of the reaction. They are so defined because they have a very fast reaction kinetics.

The NO_x production processes have been studied in depth with the "Fuel NO_x" mechanism but still today it is a mechanism that is not well defined (Khan et al., 2009).

Scholars today are in agreement with summarizing the reaction so truthfully in a simplified way as represented in Image 7.

In the reaction zone, different free radicals come into play (HCN, N, CN^- and NH) which, however, have a double reaction path, so having a competitive route as mentioned above.

This NO_x formation mechanism is called "Fuel-NO" and is a mechanism that often occurs in boilers like the one used in this study. This happens because the temperatures inside the combustion chamber are usually too low (800-900°C) for the NO formation thermal mechanism to take place (Verma et al.,2013; CEN / TS 15150: 2005).

In this study different fuels composed of biomass and their nitrogen content were analysed. The emissions of the combustor exhaust gases and therefore the NO_x content were analysed and it was found that depending on the type of fuel there would be different percentages of nitrogen and consequently different emissions of nitrogen oxides. Indeed, taking into consideration the study of Jensen (1995) has been shown that the concentrations of these two volatile species depend on the volatilization and on the combustion temperature (Khan et al., 2009).

2.6.4. Volatile organic compounds (VOCs)

Volatile organic compounds (VOCs) are a wide range of carbon-based organic chemicals. They are found in various artificial solids and liquids or already present in nature and evaporate easily. The most known VOCs are: benzene, toluene, xylenes, styrene, acetaldehyde, formaldehyde, naphthalene, limonene.

Currently the laws regulate VOCs, especially in indoor environments, where concentrations are the highest especially in the case of limited ventilation. Typical external sources, on the other hand, include emissions from the oil and gas industry, the use of solvents and transport.

VOCs are a class of pollutants with very different characteristics and some therefore also with different impacts on the environment and on human in terms of toxicity (Fuselli, 2013).

Many studies have been carried out on this type of pollutants since the danger has been found despite the fact that today there are no common and specific standards that regulate their emissions. This is also due to the lack of measurements of indoor air quality in many countries and the diversity of sampling in existing studies (Sarigiannis, 2011).

Wood combustion affects VOCs concentrations in the ambient air by their emission as gaseous pollutants or particulate (Monks et al., 2017). Many research have studied the combustion emissions of industrial and domestic biomass and their impact on the environment (McDonald et al., 2000; Wang et al, 2014). In domestic, or more generally closed environments, where wood is the predominant heating fuel, wood stoves have been shown to contribute up to 80% of emission of fine environmental particles during the winter (Leese, 1989). It is appropriate to specify that the percentages of gas emissions from the combustion of wood and all the particles deriving from it are strongly dependent on the chemical and physical composition of the fuels and the combustion conditions (McDonald et al., 2000).

2.6.5. Advantages and disadvantages of co-combustion of RDF pellets and biomass

Refused derived fuel (RDF) or solid recovery fuel (SRF) is the result of specific mechanical processes applied to waste. Specifically, the latter are those destined for landfills.RDF / SRF must have the technical and economic characteristics for generations of industrial energy.This type of waste, alternatively, has been used as fuel in waste-to-energy plants thanks to their chemical and physical characteristics. In fact, they have a high intrinsic heating value that allows the growth of the thermal efficiencies of the aforementioned systems (Massarini and Muraro,2015).

Despite the technical challenges, the co-combustion of SRF with wood pellets or other biomass material has gained interest in many European countries. However, most SRFs contain significant amounts of sodium and chlorine, some of potassium and similar amounts (but different species) of heavy metals compared to solid fossil fuels and biofuels. It has been discovered that some of these cause erosion-corrosion phenomena that occur during the operation of the boilers.

So surely there will be energy, environmental and economic benefits in replacing fossil fuels with RDF and biomass.

Energy benefits certainly include a reduction in the consumption of natural resources, sustainable reuse of biomass and a higher security of supply.The environmental benefits can be the reduction of the amount of waste destined for landfills, greater use of recycling operations and less use for landfill disposal, reduction of greenhouse gas emissions (for example CO_2, CH_4 etc ..), of fine dust and reduction of NO_x and SO_x (Del Zotto, 2015).

3. Experimental procedure

3.1. Milling Process

The milling phase is the first operation that is carried out and concerns the raw material preparation (RDF and pine wood). Processed RDF was provided by the waste treatment plant as well as the pine, but the latter already milled into fine particle. To mill the RDF a Retsch SM100 equipment was used to shred to a the meshes size of 5 mm (Image 8). The operation took about 4 hours.

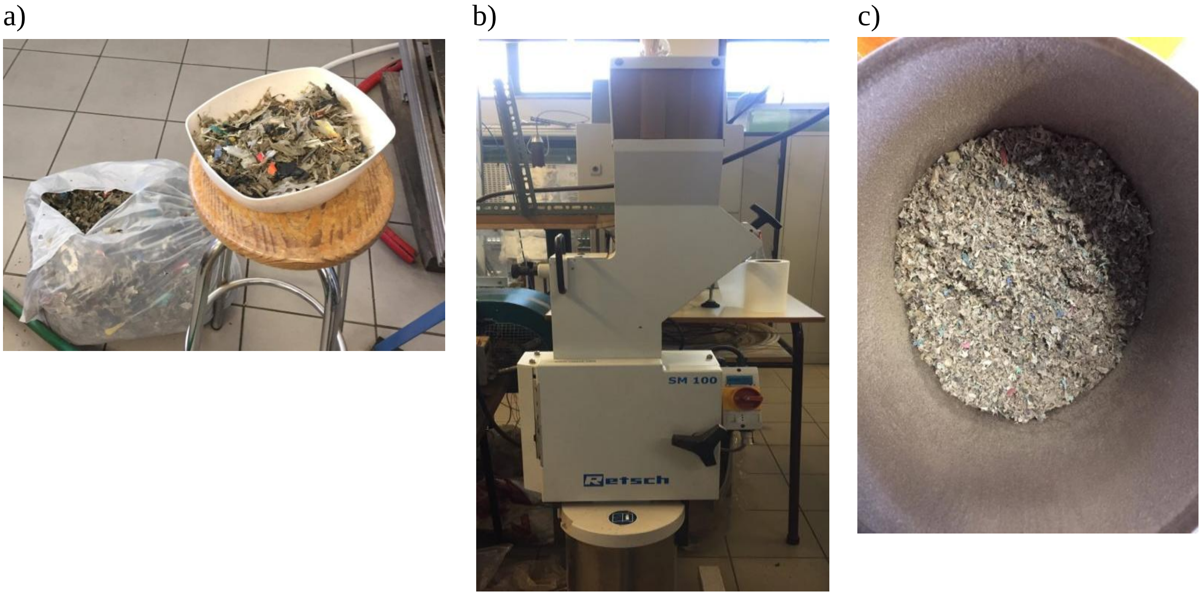


Image 8 : a) Raw material (RDF) before milling ; b) Machine for milling the raw material ; c) Raw material (RDF) milled.

3.2. Characterization of the raw material

3.2.1. Humidity content

The humidity content on a dry basis (H_{bs}) and on a wet basis (H_{bu}) was evaluated. The determination of the humidity content consists in selecting 3 samples of each material used, placing them in aluminium disks and leaving them for an hour in the drying oven (Oven Gravimeta).

According to the ISO 18134-1 standard, the mass of the sample to be inserted in the oven must be chosen and time left inside it (eg 60 minutes) at the end of which the sample must be weighed again (Balances-precise 6200D) (Image 9).

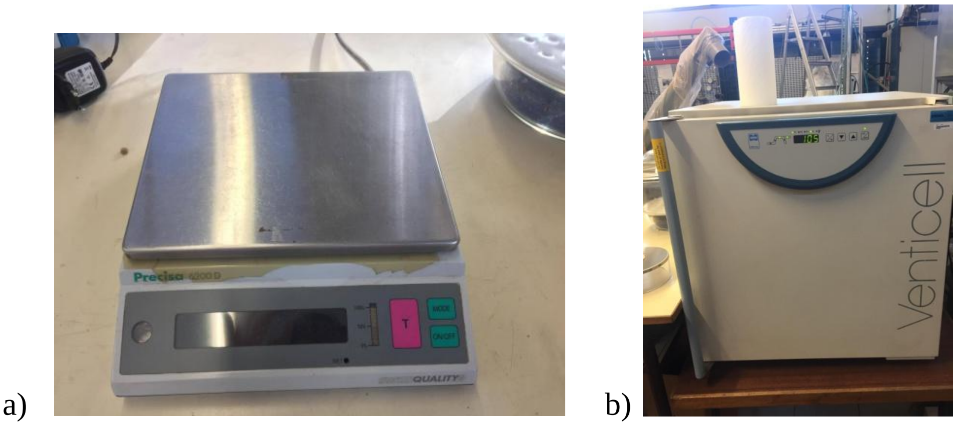

a) b)

Image 9: a) Precision balance; b) Drying oven.

It is necessary to repeat the operation until the mass is constant (eg more than 2 hours). The samples cooling previous to mass evaluation was done in a dryer (Image 10).

Image 10: Dryer.

After a constant weight is reached it is advisable to weigh them and note that their mass can be increased by a very small percentage and this is due to the fact that the material may have absorbed the humidity present in the air.

Image 11: Example of raw material the 3 samples of 5% RDF + 95% pine wood.

This operation was carried out for the 3 materials of interest: milled pine wood, milled RDF's and RDF's + milled pine wood.

The formulas used to evaluate humidity content on a dry basis (H_{wb}), as the water mass in grams per 100 grams of the total mass, which includes the water; on a wet basis (H_{db}), as the water mass in grams per 100 grams of dry matter. As percentage they are:

$$H_{wb}\,(\%) = \frac{m_w - m_d}{m_w} x100$$

$$H_{db}\,(\%) = \frac{m_w - m_d}{m_d} x100$$

Where:

H_{bs} [%] is the humidity content on a dry basis;
H_{bu} [%] is the humidity content on a wet basis;
m_w [kg] is the wet mass of material before drying;
m_d [kg] is the dry mass of the material.

3.2.2. Particle size distribution

To complete the study of the raw materials, their granulometric was carried out. The aim of the particle size analysis is to group the materials into different size classes, and to subsequently determine the weight percentages of each class, referring to the dry weight of the initial sample. The water content of the pellet has an important influence on the storage conditions and on the net heating value, on the combustion temperature and combustion efficiency. The EN 14961-2 standard establishes a maximum of 10% with respect to the humidity content of the pellet.

It should be remembered that the pine arrived already milled in the laboratory and that during storage before being delivered and during transport it probably underwent the action of heat which caused part of the water contained to evaporate.

The time and amount of energy required for drying depends on the initial humidity content of the raw materials. Some materials used in the past for research similar to this work, such as deforestation residues, are easier to dry and can have an advantage over the shredded material as regards the economy of drying.

In this research the possible effects of drying time or temperature on pellet quality were not considered (Lehtikangas, 2001).

A granulometric analysis can be carried out with two complementary methods (Romano, 2006):

1) Granulometric analysis by sieving;
2) Granulometric analysis by sedimentation.

In the present study the sieving method was used. It was done a sampling of the raw materials that allowed to obtain a sample, of adequate size (in this case 150 g) representative of the lot to be analysed. Sieves were stacked one on top of the other starting from the one with larger meshes (4 mm) up to the one with narrower meshes (<90 µm). The sieves are shown in Image 12. The aforementioned stack of sieves is placed and locked with pins on a Retsch vibratory sieve and is vibrated for 10 minutes (time set on the machine display).

Image 12: Retsch vibratory sieve.

This operation is repeated 3 times for each sample because the equipment cannot accommodate all the sieves stacked together and therefore are divided into groups of 7/8 sieves at a time. In addition, the test was repeated on 3 different samples of each raw material containing RDF used for a total of 9 samples. After the 10 minute vibration, the set of sieves is detached from the equipment and each sieve separated from the group. The mass retained by the meshes of that same sieve is weighed and the operation is repeated for each sieve. Weighing was carried out on a precise 6200 D-Mark scale, with a resolution of one milligram.

Thus the average diameter was calculated using the equation below (Kunii and Levenspiel, 1969):

$$\mathrm{d_p} = \frac{1}{\sum_\mathrm{i} \frac{\mathrm{x_i}}{\mathrm{d_{pi}}}}$$

Where:

x_i represents the mass fraction of the material particles preserved in the interval i;

d_{pi} [m] the arithmetic mean of the spacing of the meshes of two successive sieves.

The granulometric analysis operation was carried out only for the raw material composed of RDF and pine wood. The granulometric analysis of the raw material composed of pine alone was recovered from Ferreira (2013).

3.3. Pelletizing phase

The pelletizing phase is one of the most delicate phases especially for the materials used in this research. It is based above all on the use of a pelletizer (Image 13).

Image 13: Pelletizing machine.

Therefore, once the previous phases of raw material processing, such as shredding, homogenization, conditioning and stabilization of the biomass have been completed, to have a finished product with constant characteristics, the raw material can be pelletized.

The pelletizing process consists of pressing the material through a perforated die (matrix). Through the holes of the matrix the woody particulate is pushed at high pressure (up to 200 atmospheres) with suitable roller systems. With this extrusion process, which takes place by compression and heating, cylinders are created, and depending on the size of the matrix they can have a variable diameters from 2 to 12 mm and average height from 12 to 18 mm.

Once the pellets are produced, given the high temperatures with which they came out of the pelletizer, they are left to cool on a surface and then packaged. Before being packed they are sieved with a sieve with 4 mm mesh to remove the part of the material that has not compacted during the pelletization process.

3.4. Characterization of pellets

3.4.1. Humidity of pellets

The humidity of the pellets was evaluated with the same method used for the humidity of the raw material analysed. This operation was performed for all types of pellets studied.

3.4.2. Diameter and length

In accordance with the ISO/DIS 17829: 2015 standard, to measure the diameter and length of the pellets, a digital caliper (Image 14) with a resolution of 0.1 mm was used (POWERFIX Digital Calliper for 0-150 mm).

Image 14 : Digital caliper (right in its original box and left in measuring the length of a unit of pellets).

The operation consists in measuring the length and diameter of 20 units of randomly selected pellets 3 times (3 samples of 20 pellets). At least two tests have been performed for each type of pellets (see Images 15-16-17-18) and the corresponding arithmetic means were calculated.

Image 15 : Pellets of only pine (pine wood 100%).

Image 16 : Pellets of RDF’s+ pine (5% RDF’s + 95% pine).

Image 17 : Pellets of RDF’s+ pine (10% RDF’s + 90% pine).

Image 18 : Pellets of RDF’s+ pine (15% RDF’s + 85% pine).

3.4.3. Density

3.4.3.1. Mass

As described above, for each material, 20 pellets were randomly selected to determine the dimensions (length and diameter). A precise model was then weighed on a digital scale 6200, according to the ÖNORM M 7135: 2000 standard.

3.4.3.2. Particle density

To estimate the particle density of the fuel, the size method was used (Rabier et al., 2006), thanks to the ease of its application. This method is based on the ratio between the mass of the single pellet and the corresponding volume, this calculation is carried out considering it as a cylinder. The relation used for the calculation of the particle density is:

$$\rho_{pellet} = \frac{m_{pellet}}{V_{pell\,et}}$$

$$V_{pellet} = \pi \frac{D^2}{4} h$$

Where:

ρ_{pellet}	[kg/m^3] is the particle density;
m_{pellet}	[kg] is the mass of the pellet;
V_{pellet}	[m^3] is the volume of the pellet;
h	[m] is the pellet length;
D	[m] is the pellet diameter.

3.4.3.3. Bulk density

The bulk density follows on the basis of EN 15103: 2009 and it measures the density of fuel pile's with voids between pellets.

The pellets are poured from a height of 200 to 300 mm into a cup (Image 19), with a volume of five liters usually. In this study a cylinder cup of 800 mL and a defined diameter-height ratio was used, until the cylinder is full and a cone of pellets was formed.

Subsequently, the cup it is gently bumped onto a hard surface to consolidate the wooden pellets (ENplus-handbook-3.5.11).

Image 19: Cup containing pine pellets used for the determination of bulk density (V = 0.0008 m^3).

The bulk density (BD) will be calculated using the following formula:

$$BD = \frac{m_1 - m_2}{V}$$

Where:

BD	[kg/m^3] is bulk density;

m_1	[kg] is the mass of the empty container;
m_2	[kg] is the mass of the full container;
V	[m³] is the net volume of the measuring cylinder.

Subsequently, the sample material is poured and mixed with the remaining wood pellet before the procedure is repeated. An average value will be generated from the results of all measurements (ENplus-handbook-3.5.11).

3.4.4. Fine dust content

The experimental procedure is done with a sample of about 500 (± 10) g. Subsequently, the quantity of fine material will be separated with a 3.35 mm sieve Retsch (Norm: ASTM; M.W: 3.35 mm; Apertures: 200 mm x 50 mm). The sieve is shown in Image 20.

Image 20: Sieve used for the evaluation of fine dust content and mechanical durability (3.35 mm).

According to ISO 3310-1: 2000, to have a more precise analysis, the sieve must be 3.15 mm but in this research the 3.35 has been tried for technical laboratory problems.

Sieving can be achieved by shaking the sample in 5-10 circular movements using a sieve with a diameter of about 40 cm. Then the sieved particles will be weighed and the amount of fine material (F) will be calculated as follows:

$$F = \frac{m_A}{m_E} * 100$$

Where:

m_E	[kg] is the mass of the sample before sieving;
m_A	[kg] is the mass of sieved particles.

3.4.5. Mechanical durability

According to Winowiski (Boman, 2003), the method most commonly used in feed production industries (such as pellets) for assessing durability and therefore the content of fine dust in the United States is precisely the method of tumbling. Many experts in the field have carried out studies changing some aspects of the tumbling method such as rotation speed, time, size of the sieves (for fine dust) and the quantity of samples used for the tests (Sippula , 2010;Wiinikka , 2006).

There are two other methods used for the evaluation of mechanical durability and fine dust content and are the Holmen method which simulates the pneumatic movement of pellets and the Ligno tester which uses air to circulate pellets inside a chamber perforated from which the residues come out.

The Holmen tester is more used in Europe than in North America because it simulates common pneumatic conveyors in European feed mills. The sample used in the Holmen tester is smaller (about 100 g) unlike the tumbling method which requires samples of about 500 g. Furthermore the Holmen tester has a stronger impact on the durability given by the execution method and therefore produces more fine powders and therefore a slightly lower durability. Both types of tests were compared with the tumbling test and it is possible to study the topic in several documents (Boman, 2003; Sippula, 2007; Verma, 2011).

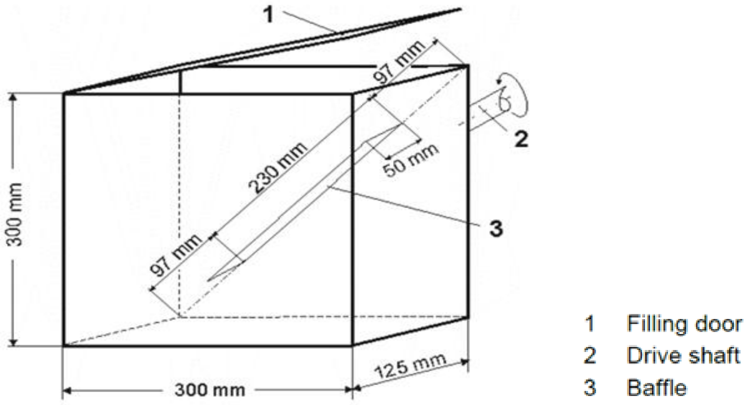


Image 21 : Aluminium (or steel) container for mechanical durability assessment.

A test portion of (500 ± 10) g is taken. The samples are weighed to the nearest 0.1 g and placed in the pellet tester (Image 21).

The standard ASAE S 269.4 describes the use of a rectangular aluminium or steel container with internal dimensions of 300x300x1259 mm and a deflector with dimensions of 230x50 mm.The test consists in rotating the sample at (50 ± 2) revolutions per minute for 500 rotations.

The sieving of the test portion after the durability test procedure will be carried out in such a way as to obtain that the particles are separated avoiding the creation of new fine particles. This is done using a sieve as described for the evaluation of fine powders. Sieving is performed by shaking the sample in about 5-10 circular movements. Subsequently, the remaining wood pellets will be weighed and the mechanical durability will be determined using the following formula:

$$DU = \frac{m_A}{m_B} x100$$

Where

DU [%] is the mechanical durability;

m_E [kg] is the pre-sieved pellet mass before the handling process;

m_A [kg] is the mass of sifted wood granules after the handling process.

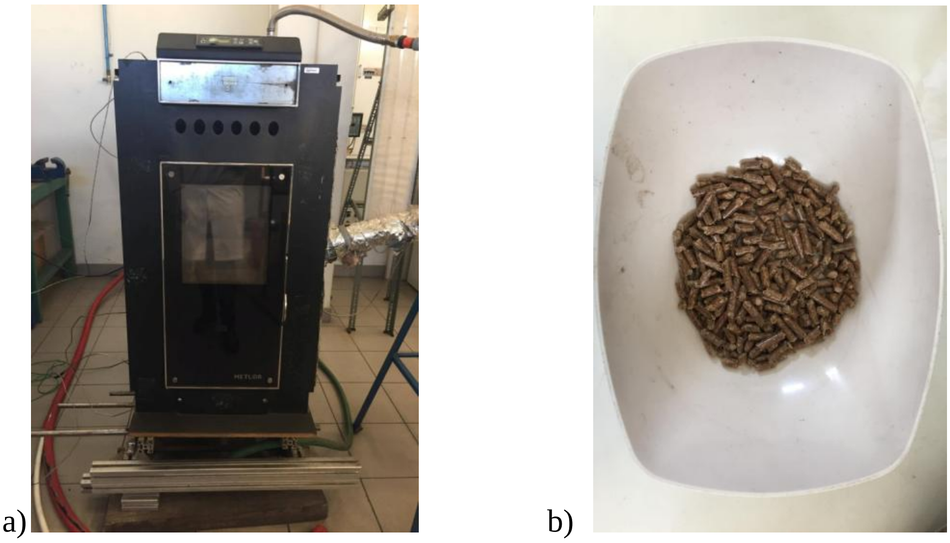
3.5. Burning Tests

3.5.1. Experimental setup of burning tests

So far the combustion of biomass in the form of pellets has been extensively studied. In particular the combustion of pine wood pellets which is the most used biomass. The pellets formed from this type of material are certified according to ENplus (EN 14961: 2011).

The apparatus used and shown in Image 22 has the following characteristics:

- Domestic *20 kW Meltor* model pellet stove with forced draft fan;
- Control unit for flue gas analysis model *Testo 350*, which deals with the analysis of combustion gases and the measurement of emissions. The *Testo* 350 analysis unit contains a sensor for O_2 measurement. Sensors can be connected for the detection of CO, CO_2, NO and NO_x;
- 8 channel thermocouple data logger Pico (*Model USB TC08*).;
- 3 K-type Thermocouple (chromel–alumel) with a sensitivity of 41 µV/°C. It has a wide variety of probes are available in its −200 °C to +1350 °C range (ASTM,1993) and a thin wire with class 1 tolerance for optimal precision for the evaluation of temperature;
- VOCs *PhoCheck Tiger* model analyser. The operation consists in the aspiration of a sample of gases emitted by the combustion. Of these, the analyzer records the quantity of VOCs ($\mu g/m^3$) emitted every 10 seconds.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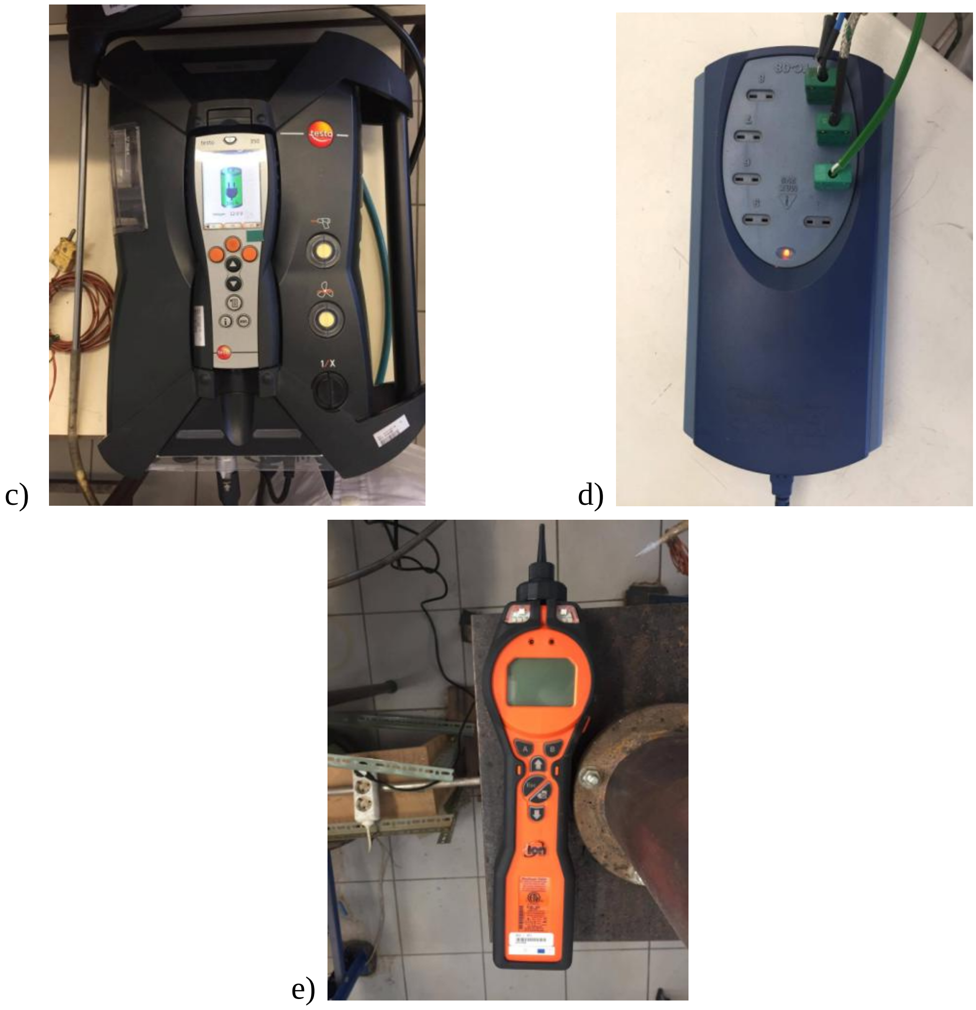


Image 22: a) Pellet stove Meltor of 20 kW : b) Pellets of pine (100% pine wood); c) Combustion analyzer (Testo 350); d) Thermocouples for evaluating the temperature of the water entering, leaving the stove and the gases emitted; e) VOCs analyzer.

The pellet boilers can be of different types and cover a wide range of nominal powers usable in the field of domestic, industrial or special applications, with applications below 10 kW, up to several MW (Fantozzi, 2010). In this particular study it is a domestic pellet boiler with a nominal power of 20 kW was used. The boiler was equipped with a hopper equipped with a screw that allowed the pellets to be introduced into the combustion chamber at equal time intervals (the feeding speed can still be regulated) (Dias, 2003).

The boiler water was turned on in a plate heat exchanger cooled by an external hydraulic circuit. The water mass flow rate was measured using both a Venturi flow meter and a turbine which were connected to the National Instrument LabVIEW 8.6 software via an NI USB-6008 DAQ datalogger. The increase in water temperature due to the heat generated by combustion has been recorded.

From the beginning of the permanent regime phase, the two devices described above for the evaluation of the gases emitted by combustion must be activated, the Testo 350 (with an Easy Emission software) which was used to measure the gas composition of discharge: O_2, CO, CO_2 and NO_x and VOCs PhoCheck Tiger for VOCs evaluation. The sampling tubes were connected to the exhaust hood. All the equipment is kept running for about 20 minutes of the steady state, ideal time for a complete evaluation. The complete operation of the pellet stove used is explained elsewhere (Ferreira, 2013).

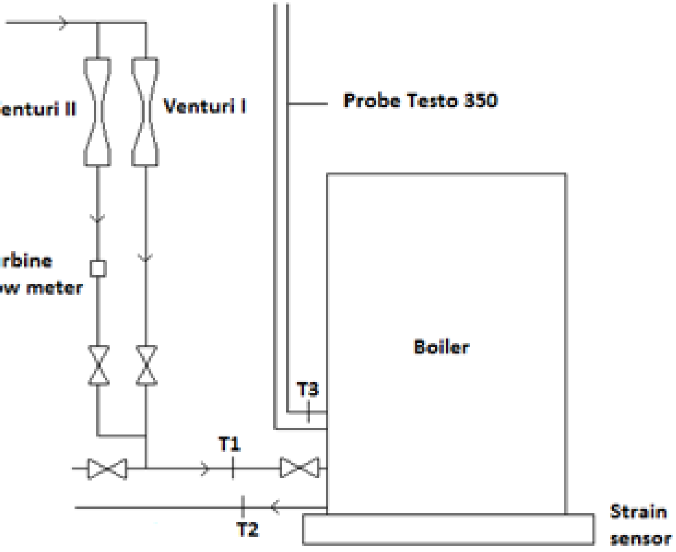


Image 23: Experimental set-up (scheme) Performance measurements.

3.5.1.1. The thermal load

The thermal load, in the experimental set-up of this stydy, indicates the quantity of energy that is dispersed to maintain a room at a predetermined value of temperature and humidity. It is possible to distinguish the sensible thermal load, which is made in relation to temperature monitoring (heating or cooling) and the latent thermal load that is instead made in relation to humidity (humidification or dehumidification). Being a power it is measured in Watts (W) and is a dynamic quantity, which varies over time due to both external (external climate) and internal (internal microclimatic conditions) factors (ASHRAE Handbook, 2009;AICARR, 2010).

The thermal power supplied to the boiler (thermal load) can be set according to the requirements. It can be calculated (according to EN 14785, 2006):

$$\dot{Q}_{provided} = \dot{m}_{pellet} \, LHV_{pellet}$$

Where:

$\dot{m}_{pellet}$	[kg/s] represents the pellet mass flow rate;
LHV_{pellet}	[kJ/kg] is the lower heating value of the pellet.

The “high” thermal load corresponds to the maximum power of the boiler that is the maximum flow of fuel supplied to the combustion chamber. Otherwise it will be the "low" thermal load.

3.5.2. The combustion test

Three tests were performed for each type of mix (5% RDF, 10% RDF and 15% RDF) and also for pine pellets. A total of 16 tests were carried out, but only 12 were taken into consideration due to technical problems with the execution of the remaining four. Each test was performed with the same methodology. The first step was the choice of the mass to be burned (from 3 to 5 kg).

Then the necessary functions were set on the different equipment: the "high" thermal load in the boiler, the connection of the three thermocouples connected to the datalogger, two to evaluate the inlet and outlet water temperature and one to evaluate the discharge temperature gas from the boiler.

After loading the fuels in the hopper, the boiler was activated and at the same time the acquisition programs for recording water and gas temperatures were powered on.

The data useful for the research were collected during the permanent regime of combustion. It involves an ignition phase of the granules, which fall at constant time intervals inside the stove and undergo ignition, which is followed by a constant increase in temperature - the transition regime. After about 20-25 minutes, observing the curve built by the PicoLog program, it can be noted that the temperature has reached a peak (high) beyond which it undergoes small variations and therefore reaches the steady state phase, or a phase in which the temperature is almost constant.

3.5.2.1. Thermal efficiency of the boiler

The thermal efficiency η_T is given by the ratio between the "useful thermal power" and the thermal power of the fuel. It compares the energy absorbed by the water with the energy released in the fuel combustion and it’s evaluated according to the equation:

$$\eta_T = \frac{\dot{m}_{H2O}\ cp_{H2O}\ \Delta T}{\dot{m}_{pellet}\ \ PCI_{pellet}}$$

Where:

$\dot{m}_{H2O}$ [kg/s] is the mass flow rate of water supplied to the boiler. The considered data for further calculation are only what concerns the stationary regimecp_{H2O} [kJ/(kg °C)] is the specific heat of the water at medium temperature which has a value of 4.18 (kJ / (°C kg)) which is the mean value considered for the temperature range of the water;

ΔT [°C] is the difference between the average in and out water temperatures from the boiler in the stationary regime;

$\dot{m}_{pellet}$ [kg/s] it is the pellet mass flow rate that in this study is evaluated by the difference of the initial and final mass of the pellet in the hopper;

PCI_{pellet} [kJ/kg] is the lower heating value (LHV) of the pellets and depends on the type of pellet. The higher heating value (HHV) of the fuels was provided with the study of the final analysis by burning in the calorimeter. From the HHV the LHV was then been calculated (as shown in the following paragraph).

3.5.2.1.1. The lower heating value (LHV)

It was necessary to calculate the lower heating value (LHV) to evaluate the thermal efficiency of the boiler (as can be seen in the equation of η_T).

The EN 15400: 2011 standard provides the equation for calculating the PCI expressed in kJ / kg . It is:

$$LHV = HHV - (206 * (\%)Hydrogen)$$

Where:

HHV	[kJ/kg] is the higher heating value;
$(\%)\ Hydrogen$	[%] is the total hydrogen percentage of the material.

3.5.3. Gas emissions

The gaseous emissions are all recorded by the same device (Testo 350) which supplies the O_2, CO_2, CO, NO_x and NO values detected inside the stove during the entire test. Some of these values must therefore be compared with the EN 14785: 2006 standard which sets the CO limits at 13% of O_2 allowed for release into the atmosphere. This correction is performed to compare the values having the same oxygen base, which is not the case without this correction (page 62) due to the different supply of air for combustion. The calculation is made with the equations reported by the EN 14785 standard:

$$CO\ \ 13\%\ of\ O_2\ (ppm) = \frac{21-13}{21-O_2(\%)}\ x\ CO(ppm)$$

The same happens with CO_2, NO_x and NO although not reported in the standard:

$$CO_2\ \ 13\%\ of\ O_2\ (ppm) = \frac{21-13}{21-O_2(\%)}\ x\ CO_2(ppm)$$

$$NO_x\ \ 13\%\ of\ O_2\ (ppm) = \frac{21-13}{21-O_2(\%)}\ x\ NO_x(ppm)$$

$$NO\ \ 13\%\ of\ O_2\ (ppm) = \frac{21-13}{21-O_2(\%)}\ x\ NO(ppm)$$

Where:

$CO(ppm)$ [ppm] is the average of CO calculated based on three tests conducted on the same material;

21 [%] is the percentage of oxygen found in the air (also composed of 79% nitrogen);

13 [%] is the percentage of standardized oxygen;

$O_2(\%)$ [%] is the average percentage of oxygen calculated based on the exhaust gases;

$\mathrm{NO_x(ppm)}$ [ppm] is the $\mathrm{NO_x}$ average calculated on the basis of the three tests conducted on the same material;

$\mathrm{CO_2(ppm)}$ [ppm] is the average of $\mathrm{CO_2}$ calculated based on the three tests conducted on the same material;

$\mathrm{NO(ppm)}$ [ppm] is the average of NO calculated based on the three tests conducted on the same material.

The CO limits provided by the standard, as already mentioned, are at 13% O_2. This oxygen is by definition different from that measured during the tests (page 62). As already mentioned, the equations for NO_x, CO_2 and NO are not specified in the standard and therefore there are no regulatory limits for these elements.

It has been noticed that the emissions in ppm of CO, CO_2 or NO_x means ml_{CO}/m^3_{air} , ml_{CO2}/m^3_{air} and ml_{NOx}/m^3_{air}.

4. Evaluation of results and discussion

4.1. Characterization of the raw material

4.1.1. Humidity content

The water content of the pellet has an important influence on the storage conditions and on the net heating value, on the combustion temperature and combustion efficiency. The EN 14961-2: 2001 establishes a maximum of 10% with respect to the humidity content of the pellets.

The time and amount of energy required for drying depends on the initial humidity content of the raw materials. Some authors report that other materials such as deforestation residues, are easier to dry and can have an advantage over the shredded material as regards the economy of drying when they are used in biomass power plants.

In this research the possible effects of the drying time or temperature on pellet quality were not considered.

For the evaluation of the humidity content (% of weight in a wet base): three samples of at least 10 g from different bags containing the same type of material were dried in the oven at 103 ± 2 ° C until constant weight was reached (Lehtikangas ,2000). The percentages of humidity in the raw materials were therefore evaluated and are shown in Table 3.

Table 3: Average humidity of the studied raw materials.

	PINE (100%)	**RDFs (100%)**	**PINE:RDF 95%:5%**	**PINE:RDF 90%:10%**	**PINE:RDF 85%:15%**	
$m_{w\ (wet)}$	15	10	12,1	12,1	12,1	g
$m_{d\ (dry)}$	13,63	9,7	11,1	11,33	11,36	g
$H_{wb\ (wet\ base)}$	9,11	3	8,26	6,33	6,06	%
$H_{db\ (dry\ base)}$	10,02	3,09	9,00	6,76	6,45	%

The evaluation of the humidity content in raw materials such as pine (100%) and RDF (100%) was carried out. The same was done for the material composed of RDF and pine in the percentages 5% and 10% of RDF, but during the pelletizing phase problems were found due to the too low or too high water content of the material.

The humidity found in the material formed by 100% RDF is extremely low. This value (3% on a wet basis) is a predictable value given the composition of the material and considering that the RDF was already from some time in the laboratory and had time to dry naturally.

The of humidity of the raw material formed by 5% of RDF is around 8.6% on a dry basis and 9.01% on a wet basis, both humidity are too low. The same thing happens for the material formed by 10% of RDF that presents humidity contents in percentages that are too low and would prevent pellet production.

The first attempts at pelletizing were performed with the raw material consisting of 5% RDF: 95% pine and it was found that the material was not compacted enough and the pelletizer did not produce pellets of the desired quality.

It was therefore decided to increase the humidity percentage to around 14% by adding water, From experience it seemed the most suitable value for pelletization.

The mass of water necessary to reach that percentage of humidity was calculated starting from the humidity equation on a wet basis:

$$H_{wb}\,(\%) = \frac{m_w - m_d}{m_w} x 100 = 14\%$$

Whose inverse equation to derive the m_d will be:

$$m_w - (0{,}14\ x\ m_w) = m_d$$

This way it can be obtained the mass of water that must be added to the mass of raw material to obtain 14% humidity.

The raw material on which this operation was carried out was that composed of 5% of RDF and the one containing 10% of RDF.

Sample of raw material for pelletizing were selected:

$$m_w\ (5\%\ RDF) = 3.150\ kg$$
$$m_w\ (10\%\ RDF) = 3.382\ kg$$

The required mass of water was calculated for each bag of raw material. For the amount of material to be pelletized mentioned above, $0.513\ kg$ and $0.473\ kg$ of water was added, respectively.

The method described above proved to be inefficient since the humidity content to be reached (14%) was a hypothetical value based on pelletisation tests performed with a part of the material containing 5% RDF. This amount of humidity has proved not to be suitable for all cases. For the pellets made from mixtures the humidity is affected by the pelletisation process where some water must be added to allow the agglomeration of the materials and therefore their agglutination . In fact when the proper humidity value for pelletizing is already known, the sample already goes with the right humidity.

It can happens that, as a consequence of the pelletisation process, the material is exposed to high temperature what can lead to some water evaporation. These two factors contribute to the required humidity value in the raw material and to the humidity found in the products that result from the pelletizing process. After producing the pellets with the proposed mixtures the humidity was evaluated and is shown in Table 4.

Table 4: Average humidity in the raw material after adding water (RDF 10% + pine 90%).

PINE+RDF's (10%)		
$m_{w\ (wet)}$	12.1	g
$m_{d\ (dry)}$	9.93	g
$H_{wb\ (wet\ base)}$	17.91	%
$H_{db\ (dry\ base)}$	21.81	%

With the raw material formed by 15% of RDF it has been proceeded as in the other two cases. The humidity content of the raw material was first calculated without adding water and then the initial method was repeated, then water was added without having a preset humidity value to be reached. The humidity evaluated before adding water is shown in the Table 3. The humidity of raw material after adding water was not evaluated.

It is noted that the humidity value is lower than that of pine, which is usually around 10%, a value that in the case of material composed of pine alone is excellent for pelletizing.

4.1.2. Particle size distribution

One of the most common procedures for evaluating the particle size distribution of a raw material consists in separating the sample by sieving it into fractions of defined dimensions and weighing each, expressing the result in weight percentage. This technique has been used by different authors in different ways and in particular has been used by Mediavilla et al. (2009) o Bergström et al. to (2008) evaluate the effects of the dimensions of the raw material on the combustion of the fuel produced with it (García Fernández, 2012; Mediavilla, 2009; Bergström, 2008).

Below are the results and the respective graphs of the particle size distribution of each single sample analysed for a total of 9 tables and 9 graphs (3 samples for each type of material).

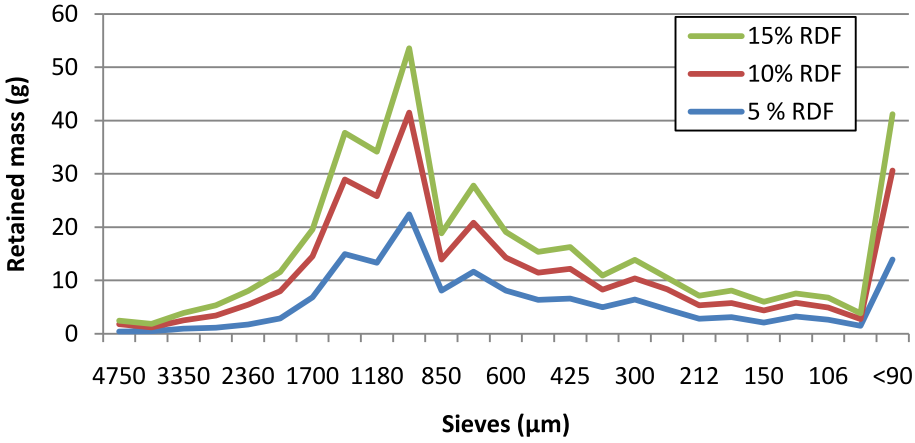


Image 24: Cumulative curve for the three types of material composed of RDFs and pine.

Table 5: Average mass retained by the sieves of different meshes (decreasing sieve value) for samples of each material.

	5% RDF+PINE	10% RDF+PINE	15% RDF+PINE
Sieves (µm)	**Weight (g)**	**Weight (g)**	**Weight (g)**
4750	0.4	1.37	0.67
4000	0.47	0.73	0.67
3350	0.93	1.57	1.40
2800	1.10	2.30	1.93
2360	1.73	3.70	2.60
2000	2.87	5.13	3.57
1700	6.83	7.67	5.07
1400	14.93	14.00	8.77
1180	13.33	12.47	8.37
1000	22.37	19.13	12.03
850	8.10	5.83	4.90
710	11.63	9.20	6.93
600	8.10	6.20	4.80
500	6.37	5.07	3.93
425	6.60	5.60	4.07
355	4.97	3.33	2.60
300	6.40	3.97	3.50
250	4.53	3.80	2.13
212	2.80	2.50	1.83
180	3.10	2.67	2.33
150	2.07	2.30	1.60
125	3.23	2.57	1.77
106	2.63	2.30	1.87
90	1.50	1.27	1.03
<90	13.90	16.70	10.57

The raw materials used in this study, as already mentioned, are of two types and have very different characteristics. In particular the pine sawdust used in this study gave a slightly greater amount of small particles unlike the RDF which presented an uneven grain size distribution. Considering this factor and humidity it can be said that long particles can adhere strongly with interlock mechanisms while small particles are often too dry and, consequently, can create weak bonds in the pelletizing phase (Bergströma,2008).

Looking at the graph in the Image 24 and the Table 5 of average retained mass values it can be seen that the distribution in these three types of material is not uniform. In particular it can be seen that starting from the graph of the material containing 5% of RDF up to the one containing 15% of RDF, there are higher values and in fact the curves seem to be strachate upwards. This is probably due to the fact that as the percentage of RDF increases in the raw material, and therefore that of the pine decreases, the mass retained in the larger sieves increases and that in the smaller sieves decreases.This is probably due to the fact that the raw material used in this research is a format made up of two different fractions (pine and RDF) which are milled with different size characteristics.

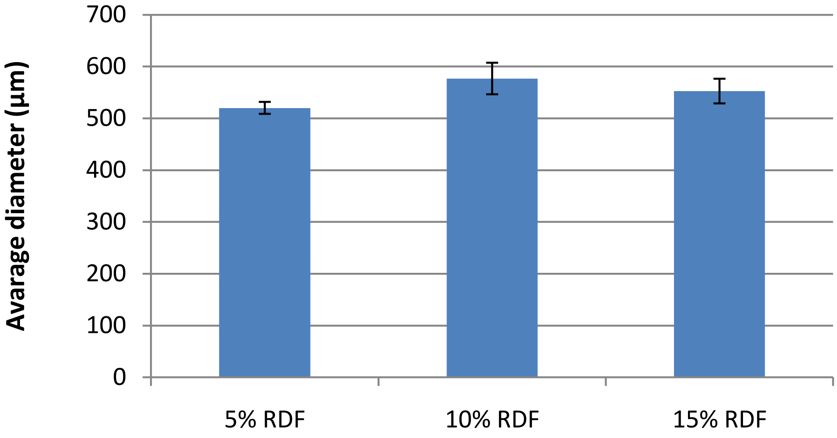


Image 25: Average of the diameter for each material containing RDFs.

The average diameter was calculated as shown in the chapter (3.2.2.) on the granulometric analysis (procedure). In the Image 25 it can be seen how effectively there is not a big difference between the average particle diameters in the three different materials formed by RDF.

The average diameter of the particles retained in the case of the raw material formed by 10% of RDF, however, is among the three major despite the expectation that this happens with the material formed by 15% of RDF. In fact, the expected trend was with the average diameter increasing as the percentage of RDF contained in the raw material grew.

The explanation lies in the fact that more than three samples had to be analysed because the samples in question, being the inhomogeneous material, may not be absolutely representative of the material. To confirm the thesis there is the standard deviation which in fact does not appear to be too different between the material composed of 10% of RDF and that composed of 15% of RDF. In fact the value obtained for 10% of RDF lies inside of the standard deviation obtained for the 15% of RDF, so it can be assumed that testing more samples will bring the values to the expected trend.

In the case of the raw material formed by 5% of RDF it can be noted that the standard deviation and the average diameter of the particles retained by the sieves are smaller than the other two cases. If the percentages of the material (5% of RDF and 95% of pine wood) is considered it is possible to understand that the composition is a possible explanation. The percentage of pine is in fact much higher than that of RDF and therefore it is not risky to say that the average diameters of the three samples are representative more of pine than of RDF.

In fact, pine has a much lower average diameter than RDF due to the composition of this one such as plastic, paper, fabrics and other materials which, although milled, can never reach the size of milled pine. The comparison can be made with the following Images 28 and 29.

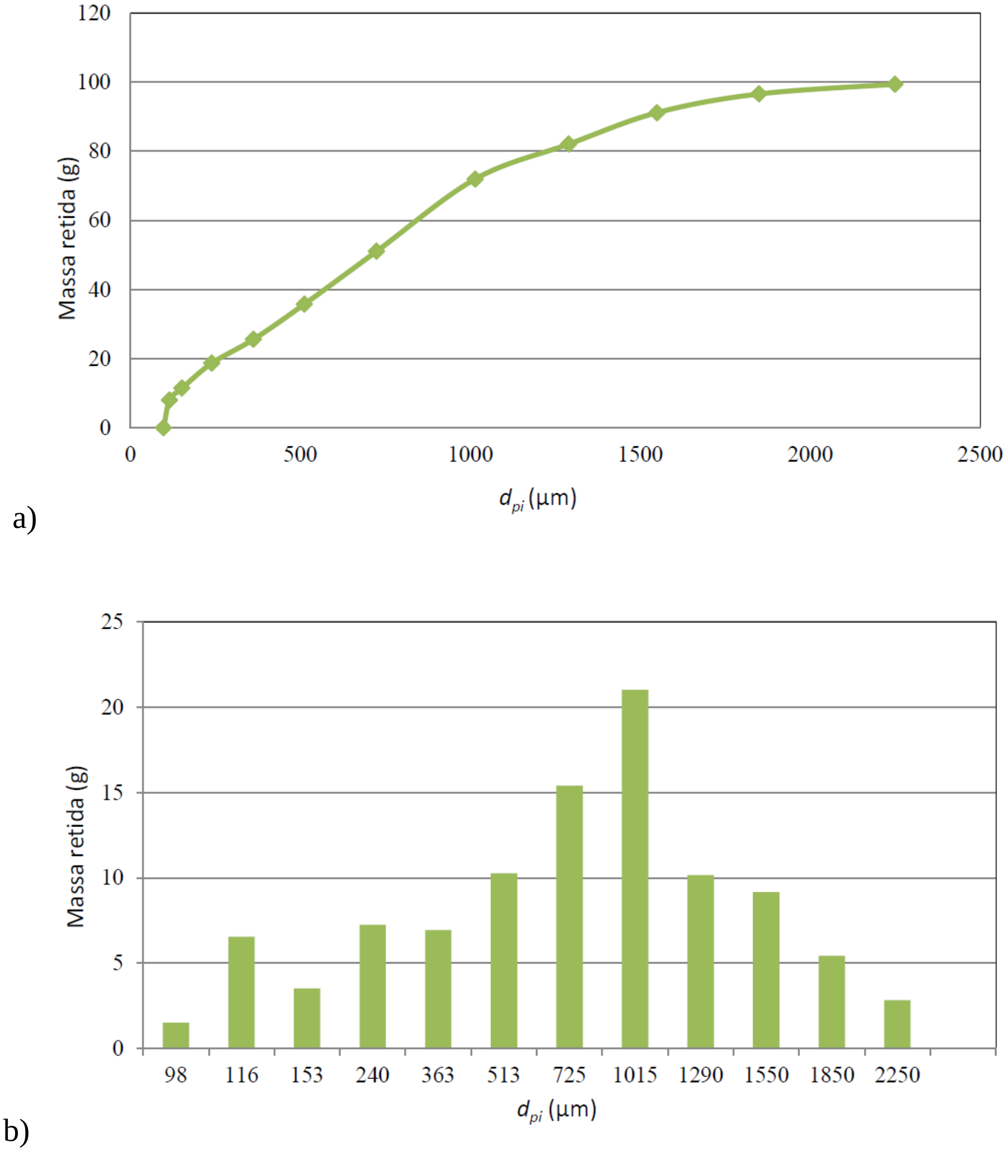
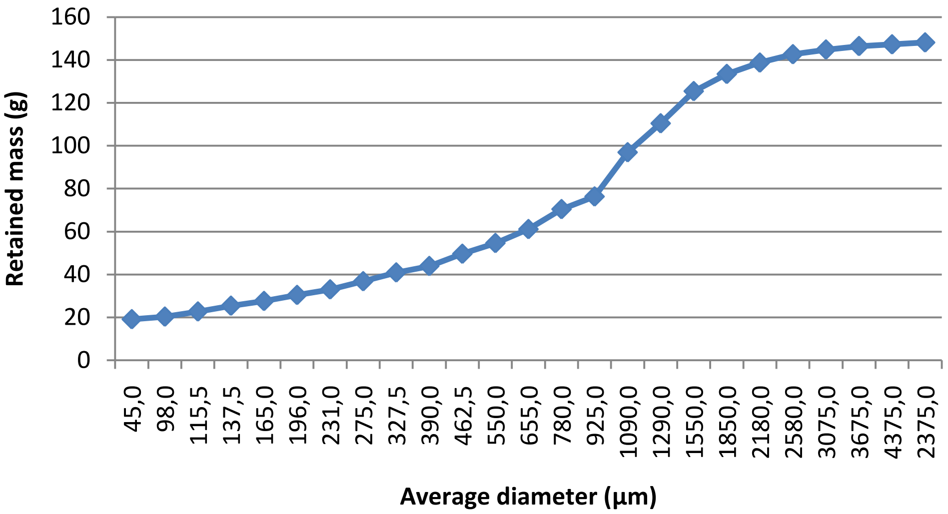
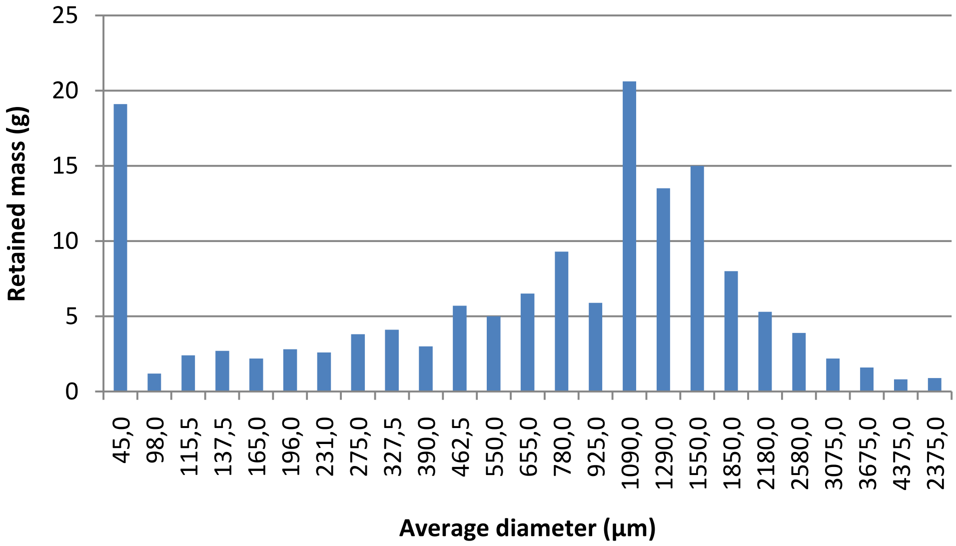


Image 26: a) Cumulative curve of the average mass retained as a function of the average diameter of the particles held by the sieves - Pine wood; b) Distribution of the average mass retained as a function of the average diameter of the particles held by the sieves - Pine wood (Ferreira, 2013).



a)



b)

Image 27: a) Cumulative curve of the average mass retained as a function of the average diameter of the particles held by the sieves - III sample containing 10% of RDFs; b) Distribution of the average mass retained as a function of the average diameter of the particles held by the sieves- III sample containing 10% of RDFs.

The graphs show (Images 26-27) the inhomogeneity of the distribution of the raw material used in this study (29) compared to the pine used in another study (Ferreira, 2013).

Furthermore from the distribution curve it can be noted that the average diameter of the pine particles held by the sieves is lower than the average diameter of the raw material with 10% of RDFs.

In the ANNEX-1 it will be possible to view the graphs representative of the other samples of each material analysed in the following study.

4.1.3. Pelletizing phase and humidity of the pellets

During the pelletizing work there was a problem with one of the physical characteristics of the raw material, humidity, which for pine pellets (those certified by the ENplus standards) is around 6%. The material used contains percentages of plastic, paper and other types of elements that are not well defined as they have not been specifically analysed and this therefore implies the use of a completely inhomogeneous material.

The humidity content of different samples was verified but unfortunately it was noted that in the pelletizing machine, which has to work at about 100 ° C, the pellets crumbled and the product returned in the form of "flour". This is due to the fact that the percentage of humidity was too low for that type of elements present inside the raw material and therefore additional water was added without knowing precisely the quantity needed.

When more water was added than needed, it was necessary to pass the material in the machine several times, which at those working temperatures allowed the liquid to evaporate. In some cases the opposite problem arose, that is, given the presence of paper inside the RDF the water was absorbed and did not evaporate during the pelletizing process.

This has influenced the mechanical durability of the final product, in fact it is lower than in the case of pine pellets which are much more compact and resistant to touch.

The Image 28, representing the average humidity content of the various materials and the average of their respective durability values, should be analysed:

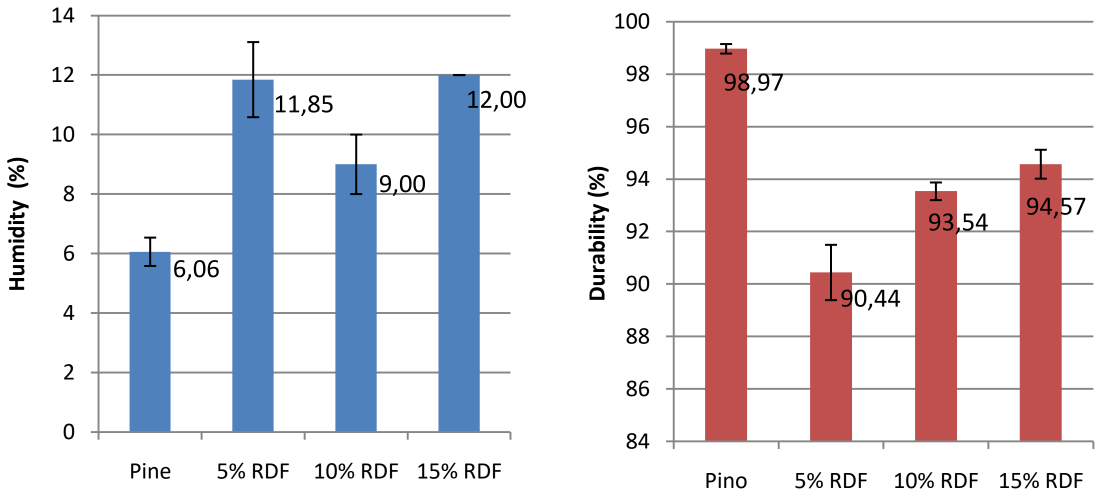


Image 28: Average values of the humidity content (%) of the four types of pellets (left); average values of mechanical durability (%) of the four types of pellets (right).

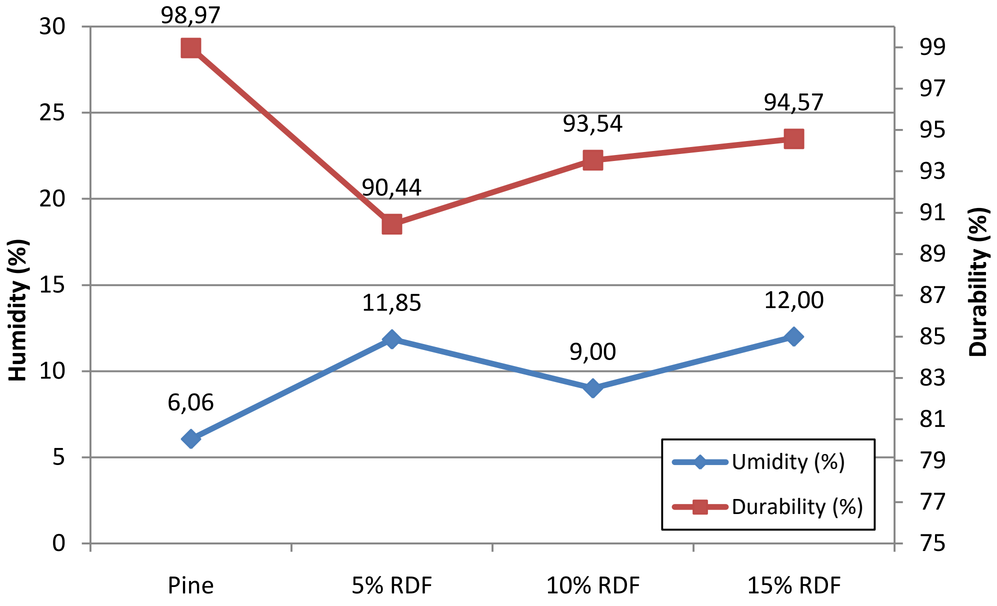


Image 29: Relation between mechanical durability (%) and humidity content (%) of the four types of pellets.

The Image 29 shows how the "rule" that links durability to the humidity content is respected in the case of pine (100%), in the case of pellets formed by 5% RDF and 10% RDF but not in case of pellets formed by 15% of RDF. In this case, in fact, the value of mechanical durability (94.57%) respects trends but the percentage does not reflect what has been said so far. The explanation could lie in the fact that the percentage of RDF in this case is more than the other two cases and consequently also the inhomogeneity of the material.

Another plausible explanation could be the pelletizing method. Returning to the chapter which talks about pelletizing and the humidity of the raw material it can be read that the tests with the various quantities of water and pelletising were carried out with the material composed of 5% of RDF and then again on 10% . The pellets formed by 15% of RDF were the last to be made and therefore on the basis of what has been said they passed less times in the pelletizing machine to avoid (as happened with the case of 10%) that too much water evaporated and therefore the machine return flour.

4.1.4. The influence of lignin

The most important chemical elements of the biomass are cellulose, hemicellulose, lignin, proteins, hydrocarbons and starch. (Romão, ?)

During the pelletizing phase of biomass pellets an important role is taken by lignin which must be within a range of values of about 20 ± 4% (Lange, Decina and Crestini, 2013) found in the literature for hardwoods. Pellets in general are surrounded by this glassy element which gives them their hardness and it has been studied that the glass transition temperature depends to a large extent on the humidity content and, under saturated water conditions, it is below the ambient temperature. The glass transition temperature of lignin also varies considerably, depending on the wood species and the humidity content and varies between 50 and over 100ºC (Stelte et al., 2011b).

Knowing the characteristics of lignin in different types of biomass is difficult and in fact is a limitation. The variations in the properties of the raw materials used during the pelletization are really complicated to predict (Lehtikangas , 2001).

4.2. Pellet characterization

The development of biomass heating systems with similar results to classic heating systems (oil or gas) was only possible thanks to the introduction on the market of pellets of uniform size and shape. The homogeneity of the pellets in terms of dimensions, water content and particle density is of great importance to obtain a completely automatic operation and a complete combustion in small boilers such as domestic ones.

Many countries have already set standards for pellets (densified fuels) by dividing them into two different types of pellets and qualities: pellets for industrial use and for small-scale consumers (Vinterbäck J., 2004).

The average values of the tests will follow and the results of each individual test are shown in detail in ANNEX 2.

4.2.1. Mass

Pellets evaluated with this work have many differences in many respects and these differences are most of the time due to humidity. In the case of mass it could said the same but as can be seen from the Image 30 this does not happen.

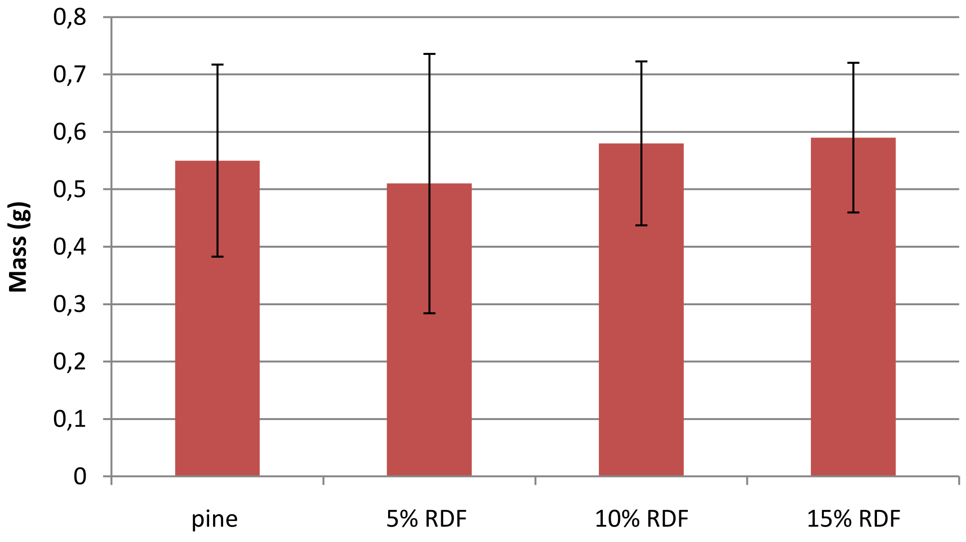


Image 30: Average mass (g) values of samples mad by 20 units of pellets (100% pine, 5% RDF, 10% RDF and 15% RDF).

The standard deviation presented by the 5% RDF pellets is greater than the other three cases. A possible explanation lies in the fact that pellets with this percentage of RDF were the first on which the experimentation was carried out. A first part of material has been pelletized without the correction of the humidity so that fuel units were more fragile and therefore with sizes, and in particular lengths, really variable. It can be said that these pellets are certainly smaller and fragmented than the pellets produced with the remaining part of the raw material.

Paying attention it is easy to be noted that even for pine pellets the standard deviation is larger than in the case of fuels formed by 10% and 15% of RDF. The reason lies in the fact that the pine pellets used in this research were purchased and not produced in the laboratory and this meant that they were handled and transported by more than one person. This has led to the billing of many units that have increased the variety of their sizes and therefore returned a greater standard variation.

4.2.2. Diameter, length and density

Pellet dimensions, both diameter and length, are important factors with regards to combustion. In particular, the rate of propagation of the reaction front through the combustion bed is lower for larger fuel particles and therefore the size is of significant importance for the temperature reached within the combustion chamber (Garcia,2014).

Both the number of pellets per unit of volume or weight, and the length of the pellet, are parameters that clearly describe the changes in physical properties and the sensitivity to breakage during transport and storage.

From the Table 7 it can be seen how the average of particle density of pine pellets is higher than those made by RDF. It is also possible to make an assessment of the decrease in the value of this parameter as the percentage of RDF contained in the material increases.

Some of the possible reasons could be the use of raw material with inadequate humidity levels and the need for their correction.Of course, too much water in the raw material causes the pellets to be less dense and more fragmented due to evaporation of water and corresponding expansion during pelleting. Moreover in this analysis it can also be said that the presence of RDFs, by their constitution, does not favor the agglomeration.

Table 6: Average values of diameter, length, mass, volume and density of 20 pellets made from the four types of material.

	100% Pine	**5% RDF**	**10% RDF**	**15% RDF**
MAIN VALUES				
Diameter (mm)	6.17±0.14	7,12±0.42	7.2±0.47	7.19±0.34
Lenght (mm)	18±4.30	15.21±5.77	18.79±3.31	19.24±3.6
Mass (g)	0.55±0.16	0.51±0.22	0.58±0.14	0.58±0.13
Vpellets (mm^3)	538.05	617.85	769.92	778.8

Table 7: Average particle density values (100% pine, 5% RDF, 10% RDF and 15% RDF).

	Particle density	
Pine	1008±135	kg/m^3
5% RDF	829±112	kg/m^3
10% RDF	771±129	kg/m^3
15% RDF	757±104	kg/m^3

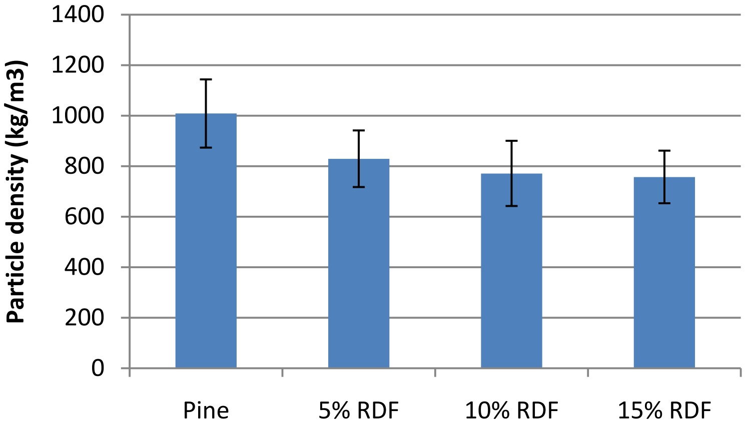


Image 31: Average density values (100% Pine, 5% RDF, 10% RDF and 15% RDF).

The comparison of tables above show some small differences between the pellets formed from different materials. The greatest comparison can be made, for the average diameter, between the pellets formed 100% from pine and among other types also composed by RDF. The former have a lower average diameter (average of 3 samples on which the analyses were performed) than the pellets also formed by RDF. This is probably due to the fact that the humidity contained in the pine and RDF mixture makes sure that the pellet unit cannot compact to its best and therefore "swells". Another plausible reason could be the composition of the RDF. There is always some expansion of the pellets soon after compaction, since the holes in the matrix are 6 mm in diameter. But it is clear that in the case of RDF pellets this expansion is higher. This may be due to the expansion of water vapor, but it is also observed that the larger the amount of RDFs the larger the expansion. It can be concluded that RDFs have an important role in this expansion and this may be due to the fact that their constitution does not favor agglomeration and may additionally provoke some elastic recovery.

This may be due to the expansion of water vapor, but it is also observed that the larger the amount of RDFs the larger the expansion. It can be concluded that RDFs have an important role in this expansion and this may be due to the fact that their constitution does not favor agglomeration and may additionally provoke some elastic recovery

The length and the mass, on the other hand, do not present particular differences in all four examples of studied pellets except in the case of 5% RDF pellets, for the reasons already presented.

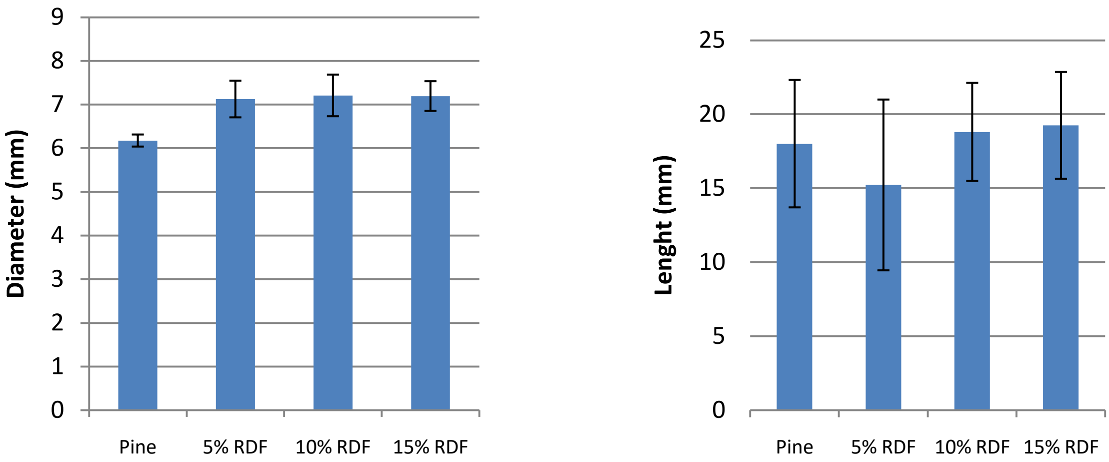


Image 32: Average diameter (mm) of the particles formed by the four different materials (on the left); Average length (mm) of the particles formed by the four different materials (right).

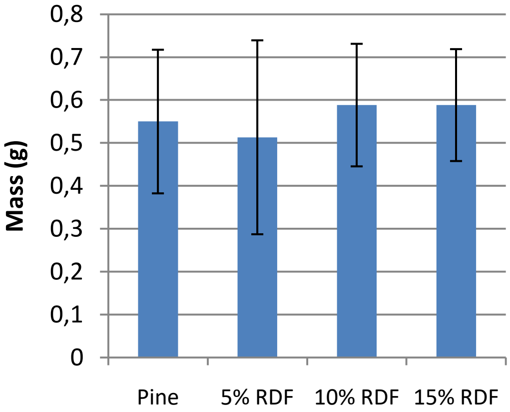
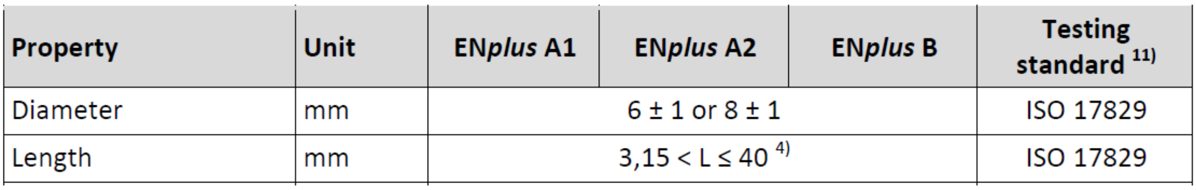


Image 33: Average mass (g) of the particles formed by the four different materials.



Property	Unit	EN*plus* A1	EN*plus* A2	EN*plus* B	Testing standard [11)]
Diameter	mm	6 ± 1 or 8 ± 1			ISO 17829
Length	mm	3,15 < L ≤ 40 [4)]			ISO 17829

Image 34: ENplus regulation for diameter and length.

Looking at the table 7 and referring to the ENplus standard (Image 34) it is possible to see that the average diameters recorded for all three samples of pellets composed of all four types of material is within the standard. The same happens for the average length recorded during analysis.

An evaluation was also carried out on the volume which is related to all the factor already explained before.

4.2.3. Bulk density

So far it has been discussed about the density of individual pellet units or average density of pellets which is different from the apparent density mentioned in the ENplus regulation.

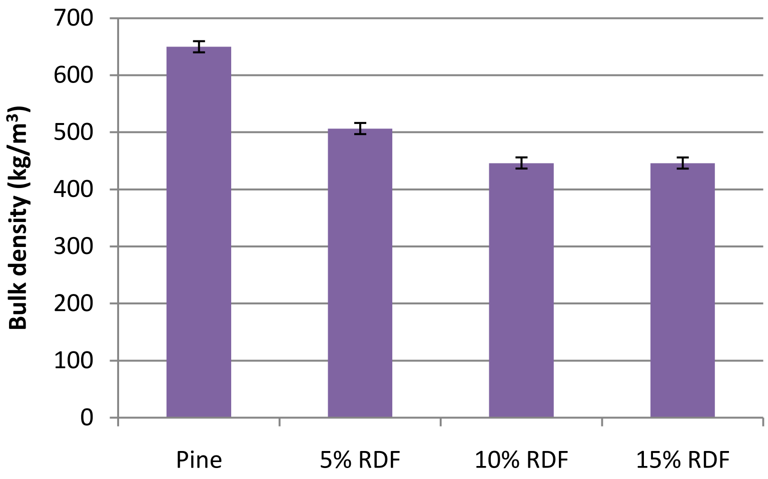


Image 35: Average values of bulk density (100% Pine, 5% RDF, 10% RDF and 15% RDF).

Table 8: Average of bulk density values (100% pine, 5% RDF, 10% RDF and 15% RDF).

	ρ (bulk density) (kg/m^3)
Pine	649.58±9,77
5% RDF	506.37±10.75
10% RDF	446.04±10.97
15% RDF	445.92±6.54

The bulk density of a given volume (800 ml) of pine pellets examined in this study is 649.6 kg/m^3 (Image 35) which is a value that falls within the limit values provided by the standard (EN 14961-2), or 600≤ρ ≤750 kg / m3. Pellets that also contain RDF do not fall within the range suggested by the standard (EN14961-2: 2001) as shown in the Table 8. In fact it is possible to notice that the average apparent density values in the case of pellets formed by 5% of RDF are 506.38 kg/m^3, pellets formed by 10% is 446.04 and for those composed of 15% of RDF is 445, 92 kg/m^3, values well below those established by the legislation.

Previously studies (Li Y, 2000; Rhén , 2005; Lehtikangas , 2001) were carried out on pellets composed of different biomasses but similar to the raw material used in this study such as sawdust, bark, fresh and stored wood residues, wood and herbaceous crops, which reported densities between 900 kg / m3 and 1200 kg / m^3. In pine pellets, in this research the density does not fall within the aforementioned field although it falls within the normative norms.

The apparent density of the pellets obviously affects the hardness of the same, the lower the density the lower their durability in percentage terms. However it should also be noted that density values too high in the pellet units increases burnout times (Obernberger ,2004).

4.2.4. Fines content and mechanical durability

The content of fine powders and mechanical durability are directly related to each other since the second is calculated from the calculation of the first percentage.

The method for assessing mechanical durability and the content of fine dust, or the method of tumbling, has already been set forth. According to Winowiski (Boman, 2003), the method most commonly used in feed production industries (such as pellets) for assessing durability and therefore the content of fine dust in the United States is precisely the method of tumbling. Many experts in the field have carried out studies changing some aspects of the tumbling method such as rotation speed, time, size of the sieves (for fine dust) and the quantity of samples used for the tests (Sippula , 2010;Wiinikka , 2006).

There are two other methods used for the evaluation of mechanical durability and fine dust content and are the Holmen method which simulates the pneumatic movement of pellets and the Ligno tester which uses air to circulate pellets inside a chamber perforated from which the residues come out.

The Holmen tester is more used in Europe than in North America because it simulates common pneumatic conveyors in European feed mills. The sample used in the Holmen tester is smaller (about 100 g) unlike the tumbling method which requires samples of about 500 g. Furthermore the Holmen tester has a stronger impact on the durability given by the execution method and therefore produces more fine powders and therefore a slightly lower durability. Both types of tests were compared with the tumbling test and it is possible to study the topic in several documents (Boman, 2003; Sippula, 2007; Verma, 2011).

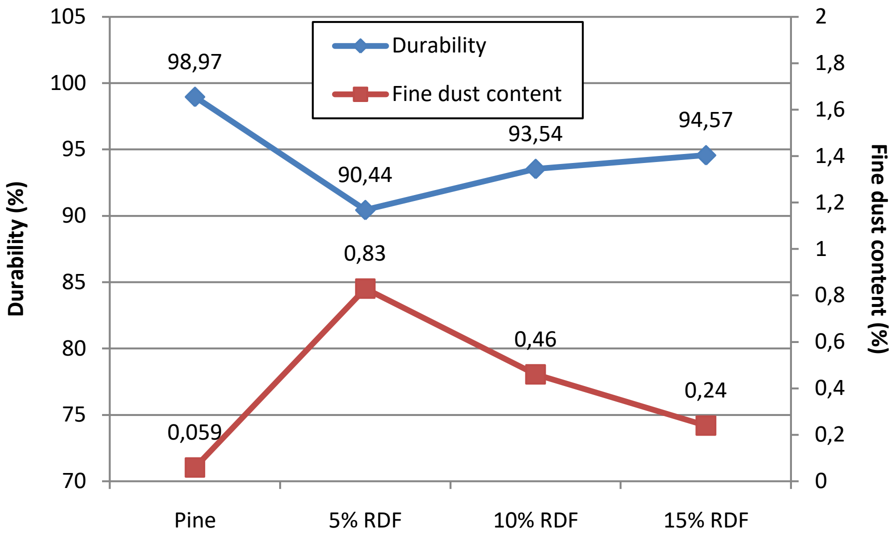


Image 36: Relation between durability (%) and fine dust content (%) of the four types of pellets analysed.

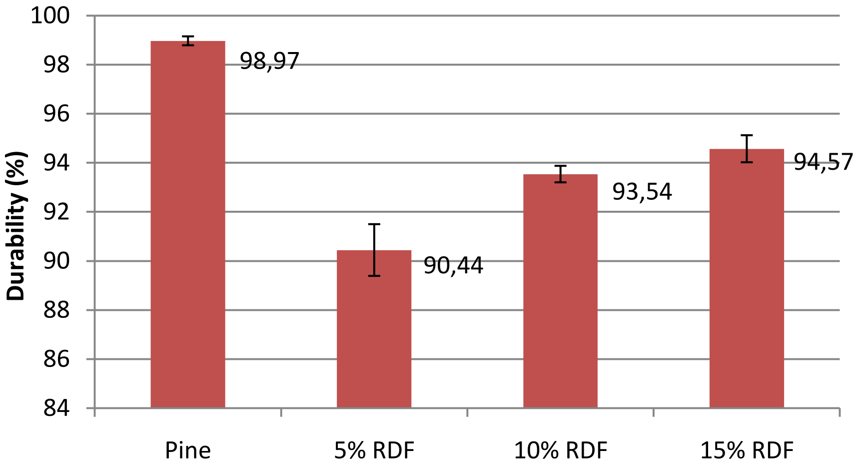


Image 37: Average mechanical durability values (100% pine, 5% RDF, 10% RDF and 15% RDF).

As can be seen from the graphs, mechanical durability varies considerably between pine-only pellets (98.97%) and those containing RDF, which, on the other hand, present the same durability values on average.. The opposite thing happens in the case of the content of fine powders which is a predictable thing knowing the way in which the tests take place and how their values are determined. Pine pellets (100%) are more resistant in terms of mechanical durability, so during the tests they lose less residues and vice versa for pellets with different percentages of RDF.

From the last graph in the Image 37 instead the difference of the standard deviations is remarkable: in the case of pine pellets and pellets formed by 10% of RDF it is very small while it varies in the other two cases. A plausible explanation could be related to the inhomogeneity of the material, which would also explain the difference between the error in the fuel containing 10% of RDF (small error) and the other two formed by RDF. Another reason could be that the pellets formed by 5% of RDF were the first to be pelletized and the material of which they are composed has repeatedly undergone variations (see humidity) and the same has happened with those of 15% in which water was added inaccurately.

Durability is closely related to the density of pellet units, discussed above: pellets with greater durability are those that have a higher density.

It was observed that pellets with high particle density of always present high durability, while pellets with lower particle density values break down easily during handling, transport and storage, increasing the amount of fines (Lehtikangas, 2001; Kaliyan, 2009).

Table 9: Values of the content of fine powders and the durability of the three pellet samples containing 5% of RDF.

5% RDF	Fine dust content (%)	Durability (%)
I sample	0,89	89,32
II sample	0,69	91,41
III sample	0,91	90,59
Average	0,83	90,44

Table 10: Values of the content of fine powders and the durability of the three pellet samples containing 10% of RDF.

10% RDF	Fine dust content (%)	Durability (%)
I sample	0,35	93,7
II sample	0,69	93,75
III sample	0,35	93,15
Average	0,46	93,53

Table 11: Values of the content of fine powders and the durability of the three pellet samples containing 15% of RDF.

15% RDF	Fine dust content (%)	Durability (%)
I sample	0,08	94,15
II sample	0,31	95,19
III sample	0,33	94,36
Average	0,24	94,57

Pellets made from 100% pine fall within the value established by the European standard EN 14961-2 which states that pellets for industrial use must have durability ≥ 97.5%.

On the contrary, the pellets made by RDF don't fall within the normative value despite the fact that in some tests similar values have been reached (Table 11-12-13).

Making reference to the same regulation (EN 14961-2) it can also be verified the values obtained from the research satisfies or not those established by it. The pine pellets used in this study were purchased and therefore certified according to the regulations. The pellets formed by RDF fall within the range established by the legislation.

4.2.5. Chemical characterization of pellets

In order to have a complete characterization of the material used in this research it was necessary to report its chemical characteristics as well as the physical ones.

The values represented in the following tables (Table 12-13-14) were very useful to analyse the combustion characteristics and emissions. These results (tables below) were object of determination of another work (Salvati, 2019).

Table 12: Proximate analysis (Salvati , 2019).

	Volatile matter (%)	Humidity (%)	Ashes (%)	Fixed carbon (%)
100 % Pine	77.28	6.84	0.66	15.22
5% RDF+Pine	72.12	11.64	1.64	14.60
10% RDF+Pine	70.97	12.22	2.43	14.38
15% RDF+Pine	68.66	13.93	2.97	14.45

Table 13: Average of Nitrogen (%) contained in four types of pellet (Salvati, 2019).

	Nitrogen (%)
Pine (100%)	0.13±0.01
5% RDF	0.08±0.03
10% RDF	0.12±0.01
15% RDF	0.04±0.03

The calculation of the percentages of carbon (%) contained in the different types of pellets was also carried out. It was carried out starting from the values obtained from the researches of Ferreira (2013) and Tomé (2018) which respectively found the value of the carbon contained in a sample formed by 100% of pine and 100% of RDF. On the basis of these values, with a simple proportion, the percentage of carbon contained in the pellets formed by 10% of pine, from 5, 10 and 15% of RDFs was obtained.

Table 14: Average of Carbon (%) contained in four types of pellet.

	Carbon %
Pine (100%)	50.61
5% RDF + Pine	50.28
10% RDF + Pine	49.96
15% RDF + Pine	49.64

4.3. Burning Tests

4.3.1. Temperature of gases during the stationary regime

The gases temperature must be analysed during the stationary regime phase which usually starts 20-25 minutes after the boiler power on. From that moment on, all the devices for evaluating the chosen parameters were activated and the data corresponding to the steady state were recorded for about 10 minutes (stationary regime phase).

Below are the graphs that show the gases temperature trends in the ten minutes, ie during the " stationary regime" phase for the tests performed on the pellets with different mixtures.

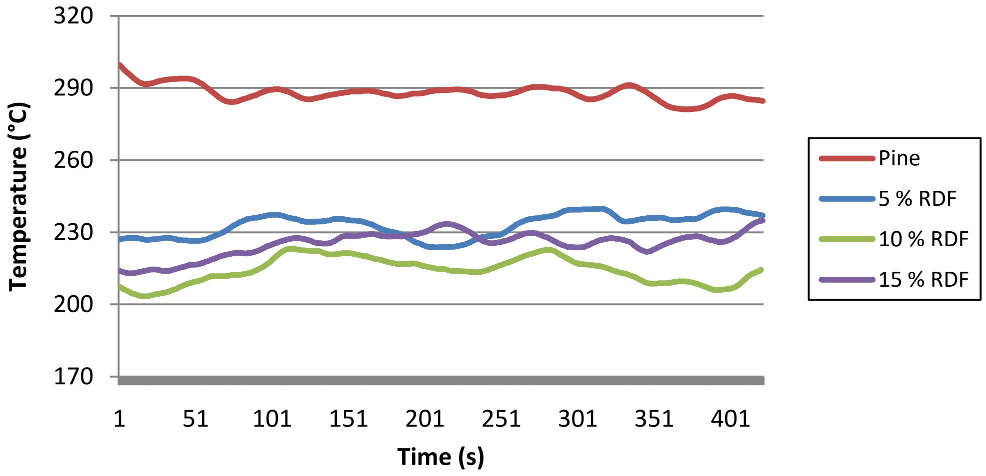


Image 38: Gases temperature evolution during the combustion of the four types of pellets in the 10 minute stationary regime.

All the tests were conducted with a "high" thermal load, consequently the temperatures reached in the stove were high given their direct correlation. During the pellet and heating pre-charge phase the exhaust gas temperature remained constant, ie at room temperature, until the pellet combustion started, as expected. Subsequently, there was a rapid increase in temperature in the initial phase due to the ignition of the pellet and the spread of the flame front. After ignition, the start-up regime consists of the propagation of the combustion front until the whole bed burns.

The temperature is usually larger in the center and this is the consequence of a greater accumulation of pellets in the center of the bed, unlike the sides where the maximum temperature is smaller (Dias, 2004).

The temperature in all four cases remained between 170 and 300 ° C but with a clear difference between the different cases. In the first case the temperature never drops below 250 ° C and only in some of its fluctuations it can be seen that it exceeds 300 ° C. In the case of pellets composed of 5% RDF it remains practically constant between 200 and 250 ° C and the difference between the three tests is almost non-existent; pellets formed by 10% of RDF have a strong decrease in temperature which is accentuated more in the case of tests carried out on pellets composed of 15% of RDF.

Once again the reason can be linked to the water content (added in some cases in not well defined quantities) starting from the pine pellets up to the ones composed by 15% of RDF.

The water content in the material to be burned influences and slows the drying phase in the stove which takes longer and consequently also slows down the ignition phase. As already mentioned, after the ignition phase there follow a series of phases: the drying of fuels, pyrolysis, gasification and therefore the final reaction in which the temperature increases up to 1400 ° C and the gases oxidize. In this last phase the pellets will no longer be solid but will become ash.

The above phases refer to a certain instant of time which is repeated for each quantity of pellet that falls into the stove within the time interval set by the machine itself. The ignition time, temperature and consequently the percentage of oxygen that must be supplied by the stove to combustion must be connected to the moisture content of the pellet. There has been talk of losses due to humidity but in the case in question there is another type of loss due to the lowering of the temperature: excess air. Looking at Table 18 it can be noted that the increase in the percentage of RDFs contained in the pellets corresponds to an increase in O_2 recorded during combustion. This phenomenon is one of the possible explanations for lowering the temperature.

After ignition, the reaction rate increases and consequently the temperature increases. The boiler control system reacts by increasing the feed rate until it reaches the selected "high load" power. As the air flow is maintained, the excess air decreases, as does the oxygen concentration in the exhaust gases (Dias, 2004).

The oxidizing reaction and in particular its speed is greatly influenced by the temperature which is a limit in the case it is very low. In reality the temperature can be a limit even if high in the case in which during the combustion there are low excess air levels since this leads to having high CO emissions due to the low availability of oxygen (see chapter on CO emissions and NO_x) (Rabaçal, 2013).

The results of each individual test are shown in detail in ANNEX 3.

4.3.2. Evaluation of thermal efficiency

The Image 39 shows the average values of the thermal efficiency and mass flow rate of pellets resulting from the combustion tests of each type of pellets. The maximum yield was obtained with the "high" load (about 61% for pine pellets of 3.44 kg/h) while the lower yield is that obtained with the pellets composed of 15% RDF (about 48.67 % with 2.24 kg/h).

Observing the values reported above it is found that for the four types of pellets, as the mass flow increases, the thermal efficiency increases as expected (Ferreira,2013).

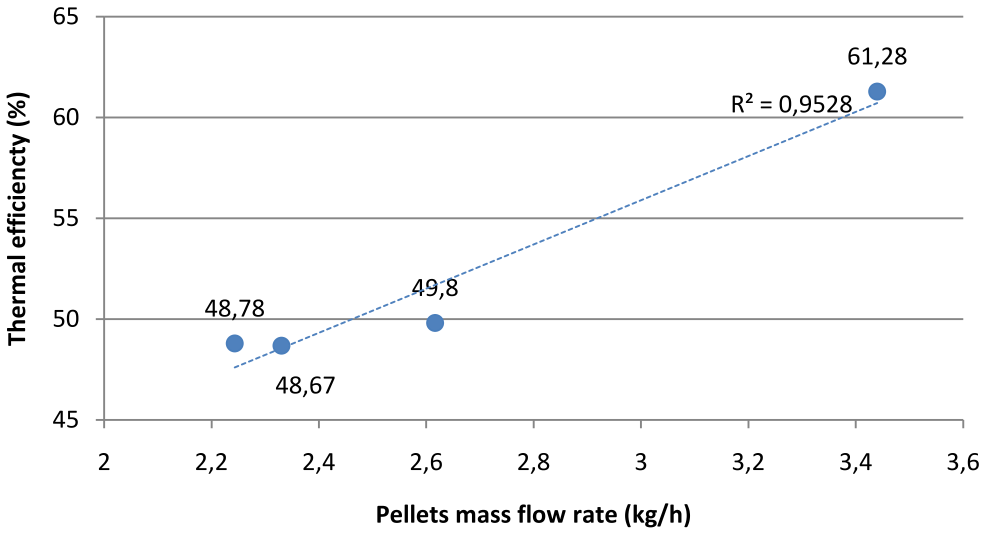


Image 39: Average thermal efficiency (%) of the four types of pellets.

In accordance with EN 14785 the average nominal thermal efficiency calculated based on at least two tests must be 75%. None of the average nominal thermal efficiency values meets the requirements of the standard. It has been only evaluated the efficiency based on water. The boiler used in this research, however, heats the ambient air also, so these are not total efficiencies, they can only be used to compare. Pine pellets are certified according to ENplus standards and in fact have, as seen in the previous paragraphs, better physical characteristics for combustion.

It is possible to find an explanation for the fact that the lowest thermal efficiency (on average) between the three types of fuels composed by RDF is that of the pellets composed by 15% of RDF. A possible explanation could, once again, be the inhomogeneity of the material. Since only 3 tests have been made for each type of material there is a large margin of error so it is not possible to establish with certainty which of the three types of pellets is better in terms of thermal efficiency. To confirm the theory there is also the strong similarity between the numbers because for all three pellets, despite the different percentages, the thermal efficiency is around 50%.

Based on the data returned by the search for thermal efficiency and recalling its objectives, it is possible to do a hypothesis, namely that the pellets formed by 15% of RDF are the best among the three tested. In fact, they are the ones that would remove the most material from the landfill, returning on average the same value of the thermal efficiency and thus guaranteeing the production of a higher amount of energy.

On the basis of this observation (looking at the equation of thermal efficiency) it can be concluded that increasing the mass flow of the pellets, consequently increases the temperature difference generated and therefore increases the thermal efficiency.

On the basis of the above, it is possible to carry out tests by setting the auger speed of the highest stove and thus increasing the mass flow of the pellets. The auger located in the hopper would have allowed a greater quantity of pellets to fall into the basket located in the combustion chamber of the stove and therefore to a greater quantity of pellets to burn. In fact, by making the ratio between the mass flows rate of the different types of pellets and their bulk densities it can be observed that they are very similar. It can therefore be said that it would be fairer to compare thermal efficiencies by setting equal mass flows.

4.3.2.1 LHV calculation and evaluation

The lower heating value of the four types of fuel has been evaluated according to the higher heating value. The latter can be summarized in Table 15:

Table 15: : Higher heating values of the four types of pellets.

	HHV (kJ/kg)
100% Pine	19713.75±695.76
5%RDF + Pine	20252±24.04
10%RDF + Pine	20683±41.01
15%RDF + Pine	21023±400.22

The last data necessary for the calculation (as can be seen in the equation for calculating the LHV) is the percentage of hydrogen (% H). For the case of pellets formed from 100% pine the data was taken from the master thesis of Ferreira (2013), which used the same pine used in this thesis and which in its text is called "Pinho A". The percentage of hydrogen contained in the sample (100%) of pine is:

$$\%\, H(bs) = 6{,}38$$

For the pellets formed by RDF the project carried out by Tomé (2018) was used, which calculated the LHV with the same method used in this work. It should be remembered that in the present study different percentages of RDF (5,10 and 15%) were used with the remaining percentages of pine and therefore 5, 10 and 15% of the percentage of hydrogen contained in 100% RDF to be considered of a sample analysed in the work of Tomé (2018).

The calculation was done for the all cases. The values are shown in Table 16:

Table 16: Percentages of total Hydrogen in the four types of pellets.

	% H_2	
	Pine	**RDF**
100% Pine	6.38	0
5%RDF + 95% Pine	6.061	0.3145
10%RDF + 90% Pine	5.742	0.629
15%RDF + 85% Pine	5.423	0.9435

Then the equation for calculating LVH was applied for each type of pellet used in this research. The calculations were made considering the different percentages, therefore for the pellets formed only by pine. The LVH values are summarized in Table 17:

Table 17: Lower heating values of the four types of pellets.

	LHV (kJ/kg)
100% Pine	18399.47
5%RDF + Pine	18938.64
10%RDF + Pine	19370.57
15%RDF + Pine	19711,50

4.3.3. CO, CO_2 and NO_x emissions

In an ideal complete combustion what will result are exhaust gases containing water, nitrogen and carbon dioxide. In the case of biomass combustion, what happens is slightly different since it contains impurities or probably occurs in conditions of improper combustion. Certainly what has to happen for a complete and ideal combustion is that there is a high temperature, a good turbulence for the mixing between fuel and comburent and a right residence time (Verma, 2013).

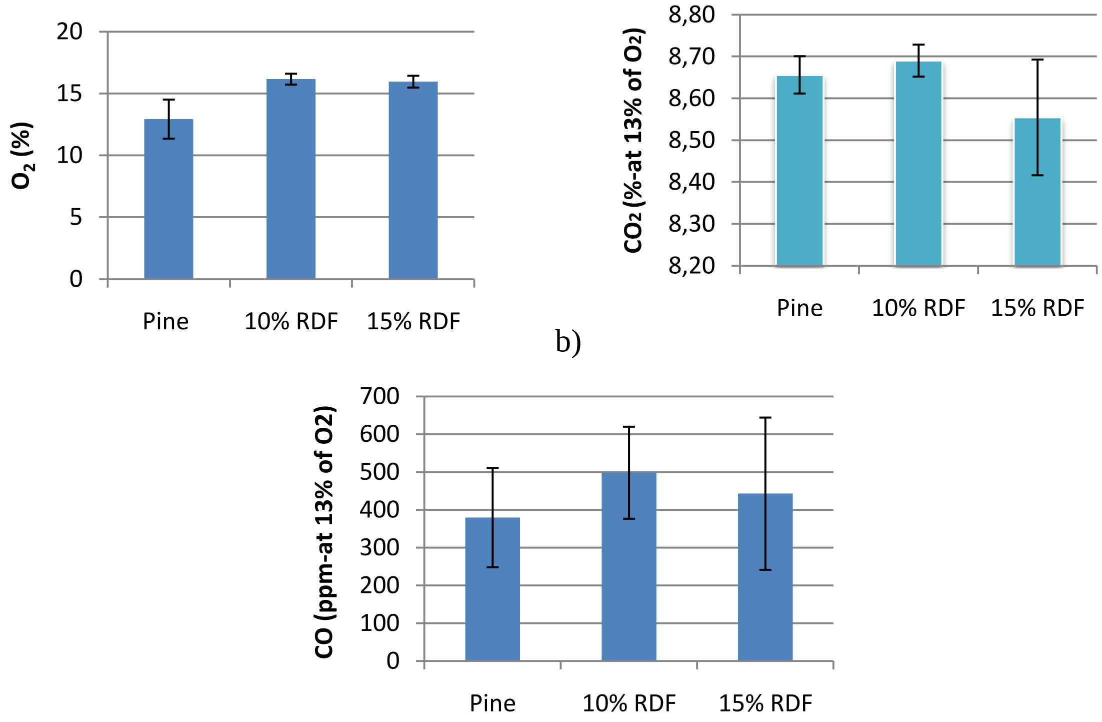
In the case study, tests were performed with only one thermal load, ie the "high" one. It is important to remember that this "high thermal load" corresponds to the maximum speed of the feed spindle that the boiler has. This implies that the only difference that can be detected is between the types of pellets burned and not between the different thermal loads set. It is not uncommon for the use of different thermal loads and different types of pellets to notice that the type of pellet has a greater influence on the gaseous emissions than the thermal load used. In several scientific studies this dependence has been demonstrated (Garcia,2014).

The CO_2 is essentially an acid oxide, its molecule is made up of a carbon atom, bound to two oxygen atoms. CO_2 is produced from carbon monoxide (CO) in combustion processes.

With regard to air pollution, reference is made to NO_x, intended as a combination of nitrogen monoxide (NO) and nitrogen dioxide (NO_2). Nitrogen monoxide (NO) is a pollutant of primary origin, produced through high temperature combustion processes; nitrogen dioxide (NO_2) is a mostly secondary pollutant, which plays a fundamental role in the formation of photochemical smog and acid rain, and is among the precursors of some significant particulate fractions.

4.3.3.1. CO and CO_2 emissions

The following Image 40 shows the averages of the gas emissions recorded during the combustion tests of the different types of pellets in the "high" load. In particular, the gases analysed are: oxygen, carbon dioxide and carbon monoxide.



a)

b)

c)

Image 40: a) Oxygen (O_2); b) Carbon dioxide (CO_2 at 13%); c) Carbon monoxide emissions (CO at 13%) for the four types of pellets.

The tests carried out on pellets containing 5% of RDF were not taken into consideration because the recorded values of the emissions are too different from each other and therefore according to what has been said about the problems that arose during their pelletizing phase, it was decided not to take them into consideration. In particular, this conclusion was reached mainly because the values should have been similar to those recorded for the combustion of pine pellets due to their similar composition (5% of RDF + 95% of pine).

After having done all the tests, the average emission values were recorded and then the emission values were corrected to 13% O_2. In this way it was possible to start from the same base and therefore from the same oxygen percentage, in order to compare them.

Table 18: Average values of O_2, CO and CO_2 for the three types of pellets.

	O_2(%)	**CO (ppm)**	**CO_2 (%)**
Pine	12.4±1.57	379.43±131.31	8.66±0.04
10% RDFs	16.25±0.43	498.00±121.75	8.69±0.04
15% RDFs	16.15±0.47	442.59±201.39	8.55±0.014

The case of pellets formed from 100% pine has that the percentage of O_2 on average is 12.4% while for pellets containing RDF it increases. In fact they will have values of 16.03%, 16.25% and 16.15% respectively for pellets containing 5%, 10% and 15% of RDF. This is probably due to mechanical durability but especially to density . Having a lower density, the mass flow rate of the fuel is lower (as verified) and therefore the excess air is higher (see paragraph 4.3.3.1.1.).

The meaning of "complete combustion" has already been mentioned, which, in order to take place, needs certain characteristics including the stoichiometric oxygen supplied by the air introduced, the time required to stay and the correct mixing of fuel and comburent.

Biomass in general does not undergo a complete combustion reaction as could occur with fossil fuels and this is due to the fact that it has different chemical characteristics (see paragraph 4.2.5.) and because of the mechanics of combustion. In the case of solid particles burning, the fuel / oxidant mixture is never perfect and the combustion is often dominated by the oxidizer diffusion mechanism. That is the reason why the burning of biomass always requires an high excess of air in order to obtain conditions close to complete combustion.

The tests in question were carried out in a domestic boiler in which the air supplied to the combustion is not in stoichiometric conditions. The values of O_2 concentrations reported are fairly high values and this is caused by the large amount of excess air supplied during the process as can also be verified by another experimental study carried out with the same boiler (Ferreira, 2013).

When the condition just described occurs the temperature decreases and there will be the formation of greater amounts of CO. The combustion will be incomplete and there will not be the time and energy necessary to completely burn the CO to CO_2. The formation of carbon dioxide therefore has a close correlation with excess air: as the excess air supplied to the combustion increases, the absolute value of CO_2 emission decreases as verified in other studies (Taraschi 1998). Since the concentration of CO_2 in the gases is analyzed in this work, the effect of the dilution must also be taken into consideration. In fact, as the excess air is higher the CO_2 gets more diluted and therefore its concentration is lower.

In other texts (Arranz,?) the combustion of pine pellets and other materials was studied and their physical and chemical characteristics and emissions were compared. The dependence on the mass flow rate of the pellets and the concentration of oxygen supplied to the combustion was observed. In that study tests were performed on different samples by varying the mass flow rate and the boiler provided a large amount of excess air. For test number 4, which has the mass flow rate (3.3 kg/h) similar to the average of the mass flows recorded in our tests (3.44 kg/h), the value of the oxygen concentration is about 14.93%. What is noted is that as the pellet mass flow rate increases it will be an increase in CO_2 concentration. It is important for the research to compare the results obtained with those established by the standard which in this case is EN 14785. It establishes limits for carbon monoxide for "reduced" and "high" thermal loads which are respectively 600 ppm (at 13 % of O_2) and 400 ppm (at 13% of O_2). As can be observed from Table 18 the only case in (on average) the CO value falls within the regulatory limit is that of the combustion of pine pellets (379.43). However, the result is no longer true if the standard deviation is taken into account, which brings the CO values well beyond those established by the legislation. The result in the case of pellets made by RDF is not positive from a regulatory point of view. However, it can be observed that the values in the case of pellets formed by 15% of RDF do not stray too far from the regulatory limits.

4.3.3.1.1. The influence of mechanical durability and temperature on CO emissions

To relate mechanical durability to CO emissions, it was considered appropriate to consider also those returned from the combustion of pellets composed of 5% RDF to validate the thesis.

As can be seen from image 41, as the durability decreases CO emissions increase.

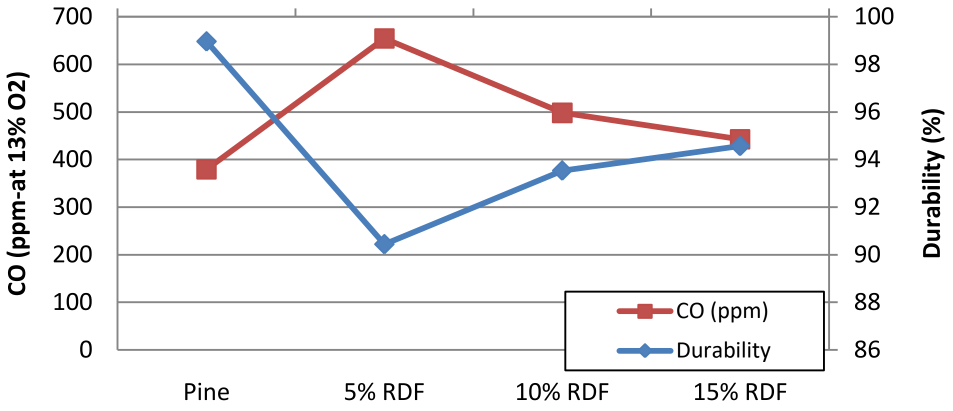


Image 41: Relationship between durability (%) and CO emissions (ppm) for the four types of pellets.

Making the correction of the CO and NO_x values at 13% O_2, as expected, it can be noted note that as the oxygen value increases, the CO emissions decrease and consequently the CO_2 emissions increase.

Referring to what has been said so far for low O_2 concentration there will be higher CO emissions values. Good combustion have low CO emissions and higher CO_2 emissions. During combustion, in fact, if the fuel has a high mechanical durability, it is verified that O_2 has more time to come into contact with the material to be burned and in particular with carbon, which leads to longer burnout times. in fact pellets with a lower durability disintegrate more easily and therefore, as the reaction surface grows, the approach of O_2 to C is facilitated. It happens that the carbon contained in the pellets has the reaction time necessary to form the

CO_2. Furthermore, if the pellets have a low mechanical durability, and therefore a low density, they are porous and this allows the O_2 to be mixed with the material more easily and a rapid combustion occurs. Having pellets with low mechanical durability, O_2 immediately comes into contact with carbon, the fuel does not burn completely and this leads to the formation of CO and the accumulation of more ashes at the end of the test. The higher the CO / CO_2 ratio, the lower the combustion rate (García Fernández et al., 2012). The chemical reactions of combustion follow:

1) Complete carbon reaction

$$C + O_2 \rightarrow CO_2$$

2) Incomplete carbon reaction

$$2C + O_2 \rightarrow 2CO$$

3) CO burning reaction:

$$CO + 0.5O_2 \rightarrow CO_2$$

There are some factors that greatly influence CO emissions and these are: gas residence time in the combustion chamber, temperature and turbulence generated in the gases (or mixing).

The largest values of O_2 released in the boiler correspond to lower values of thermal inputs which cause a decrease in the temperature of the gases generated in the combustion chamber and consequently more CO is produced (Dias, 2004).

The study was carried out as already mentioned with "high" heat load and this guarantees a greater energy available for combustion and ensures that a higher temperature is reached. This plays a very important role on the speed of oxidative reaction and in particular it appears to be a limiting factor if it is too low (Johansson, 2004).

The temperature of the gases released by the boiler and the excess air supplied to the combustion must reach an optimal compromise. The reason is that despite the mixing of volatiles and fresh air introduced is a positive factor for turbulence, too high a flow of air is a negative factor for CO emissions (Garcia, 2014).

4.3.3.2. NO_x emissions

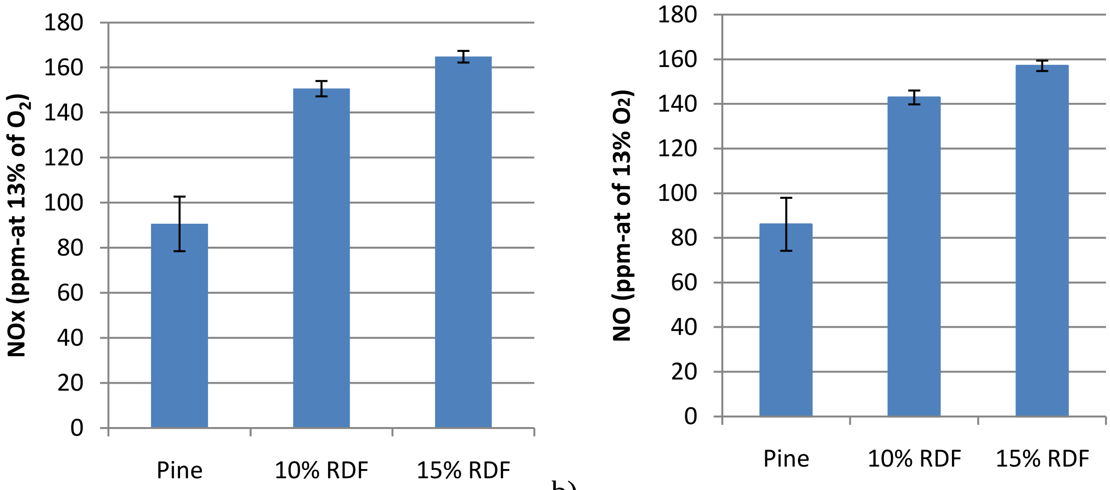
The evaluation of the nitrogen gases emissions is presented excluding the data about the 5% RDF pine pellets combustion because, as previously mentioned, the experiments results' weren't reliable.

Table 19: Average NO_x and NO values for the three types of pellets

	NO_x (ppm)	**NO (ppm)**
Pine	90.62	86.07
10% RDFs	150.65	142.91
15% RDFs	164.85	157.08

As presented before, in the chapter of pellets characterization, the nitrogen values in the various types of fuels it can be immediately noticed that they are clearly lower than the values returned by the analysis of fossil fuels (0.3-2%), as expected. They will be just as different from the N values resulting from the analysis of a RDF (Tomé, 2018) project and from the values provided by the analysis laboratory for pine pellets (Boletim de ensaios nº 516/12, 2012). In fact, in the project in which the RDFs were analysed, it appears that the percentage of N was 1.08 (%) and in pine pellets it is 0.2%.

The first study was conducted on the raw material from the landfill, the other was conducted on pine pellets such as those used in this study.



a) b)

Image 42: a) Emissions of nitrogen oxides (NO_x) at 13% O_2 for the three types of pellets; b) Emissions of nitrogen monoxide (NO) at 13% O_2 for the three types of pellets.

Taking these values into consideration, it can be reflected a trend in the figures (Image 42) in which it can be seen that as the nitrogen value contained in the raw material increases, the value of NO_x and NO also increases. In fact, it is expected that as the content of N (%) in the fuel increases, so will the NO_x and NO emissions (Arranz,?; Rabacal, 2013). In this case, looking at the Table 19 and the Image 43 one realizes that this does not happen. The table reveals that there is no clear relationship between the chemically assessed nitrogen content and the NO_x and NO values recorded during the stationary regime in the tests. A possible justification could be the inhomogeneity of the material and the fact that it may not have been properly mixed. Consequently the chemical analyses, having been carried out on extremely small samples with respect to the totality of the pelletized material, may not be representative of the actual nitrogen content.

Another possible explanation could be made by shifting the attention from the nitrogen content (N) of the material, considered until now, to that contained in the air. It can be seen that in the case of pellets containing RDFs there is an increase in O_2 and this means that the fan performs a greater "air draft". It is concluded that the reason could be sought in the excess air supplied during the boiler operation.

The results of each individual test are shown in detail in ANNEX 4.

4.3.4. Volatile organic compounds (VOCs)

The analysis of the VOCs in the gas emission was done every 10 seconds in the stationary regime around 10 minutes in the end of the essay, in order to guaranty the same conditions for all the test and data acquired. These data are shown in Image 43.

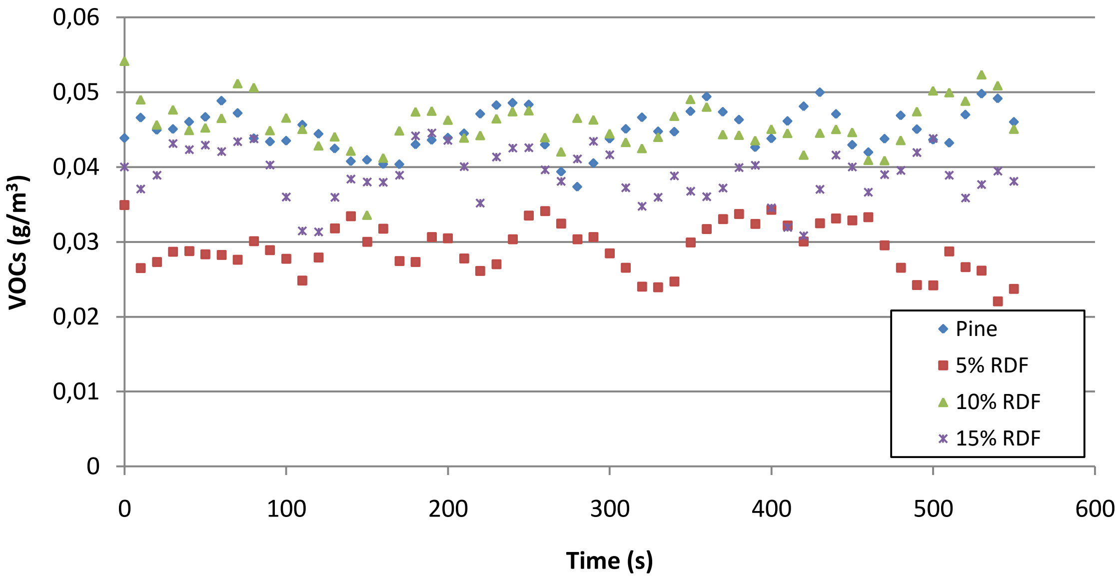


Image 43: Average of VOCs emissions (g/m^3) during a period of 10 minutes in the stationary regime.

It is possible to see that during the period of measurement, the VOCs concentrations had fluctuations probably related with the temperature and flow rate of the gaseous flow.

The data provided by the VOCs analyser were in µg/m3 but it was appropriate to transform the unit of measurement into g/kg of burned pellet in order to standardize the emissions. This calculus was carried out by exploiting the pellets bulk density and their mass flow rate as well as the gas emissions flow rate, at the temperature measured.

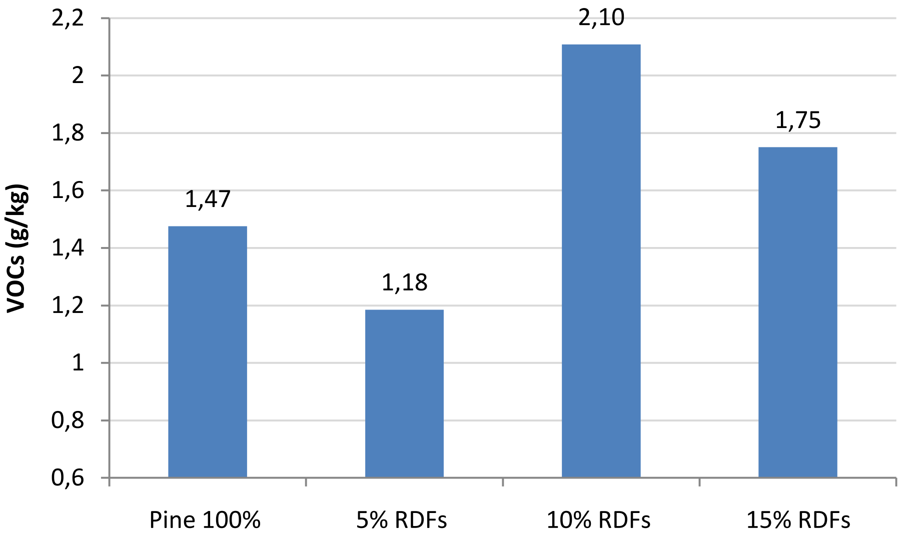


Image 44: Sum of VOCs emissions (g/kg) during the stationary regime (10 minutes).

These results are presented in Image 44 and in more details in Table 20.

Table 20: Sum of VOCs emissions (g/kg),O_2 (%) and CO emissions (ppm) during the stationary regime (10 minutes).

	VOCs (g/kg)	O_2(%)	CO (ppm)
Pine	1.47	12.4	379.43
5% RDF	1.18	15.53	-
10% RDF	2.10	16.25	498.00
15% RDF	1.75	16.15	442.58

Mcdonald et al (2000) studied the VOCs emission rates from residential wood combustion and observed from burning softwoods in the fireplace values of 5.8 g_{VOCs}/kg of fuel, with identification of over than 350 compounds, namely alkanes, halogenated compounds, furans, carbonyls, alcohols, phenols, aromatics (including PAH), among others. But most important was the identification of especially hazardous air pollutants such as 1,3-butadiene, benzene or formaldehyde. Wang et al. (2014) also studied the profile of VOCs emissions associated with biomass burning and reported about 0.98 g/kg for wood burning, with higher values for other biomass like straw. These authors also found a representative emission of oxygenated compounds in the VOCs but also the compounds profile mentioned above.

Wang et al. (2014) showed a positive dependence between VOCs emissions and CO emissions. This last observation is probably due to the higher amounts of CO and a more incomplete oxidation of volatile components. In the present research this dependence is evident (see image 45). Once again it is possible to refer to the carbon content and incompleteness of the combustion.

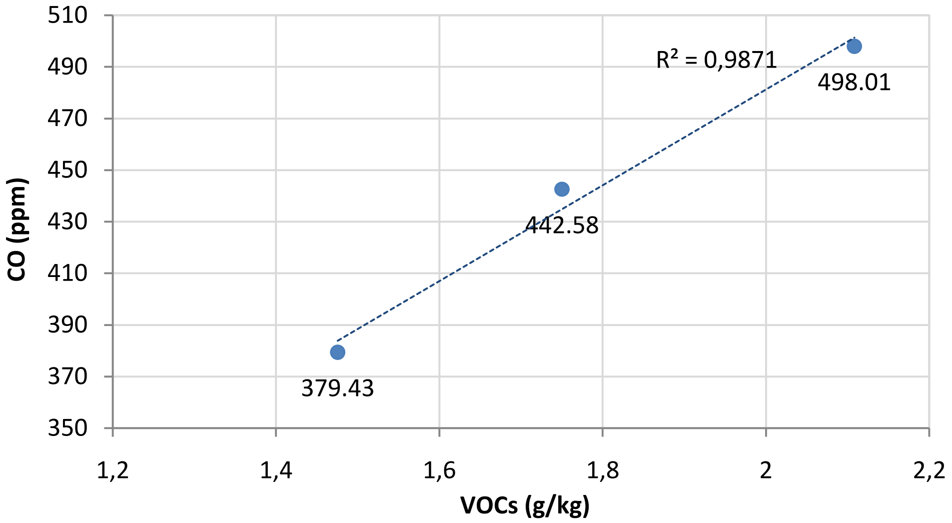


Image 45: Relation between VOCs emissions (g/kg) during the stationary regime and CO (ppm) emissions.

It is possible to link the VOCs emissions also to the O_2 percentage of the exhaust gasses (Image 46) which once again is due to the incomplete combustion conditions. As the percentage of oxygen increases, a consequent increase in the total quantity of VOCs emitted is observed.

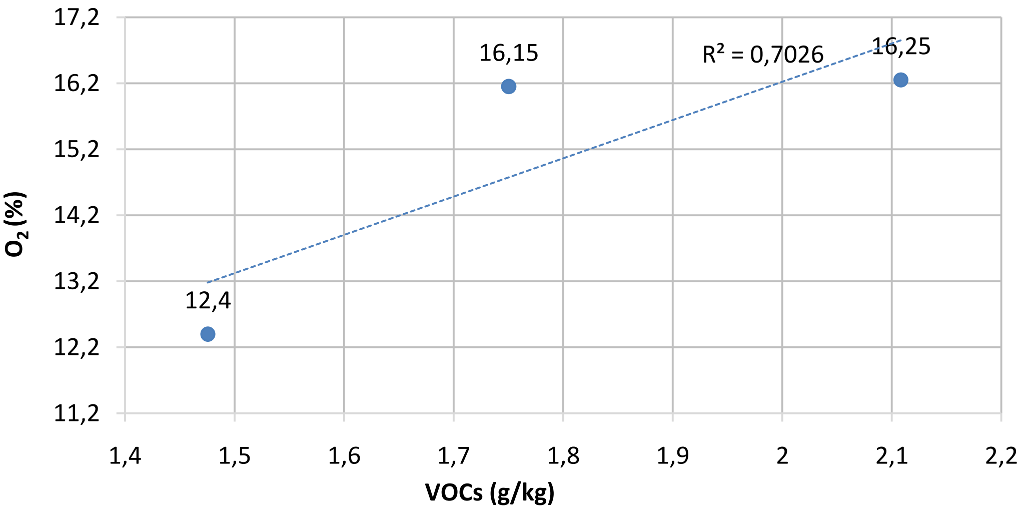


Image 46: Relation between VOCs emissions (g/kg) during the stationary regime and O_2 (%).

McDonald et al. (2000) reported that as the humidity in the various types of wood increased, the emission rate of VOCs increased 2-4 times. This probably it is related to the lower temperatures reached in the wood stove. In the present research, as can be seen from the Image 47 there is a tendency between VOCs emissions and fuel humidity. As humidity increases, the combustion temperatures are reduced, as seen, due to the energy losses that occur during combustion. Therefore there is a more incomplete reaction, VOCs emissions increase and CO emissions too as already seen.

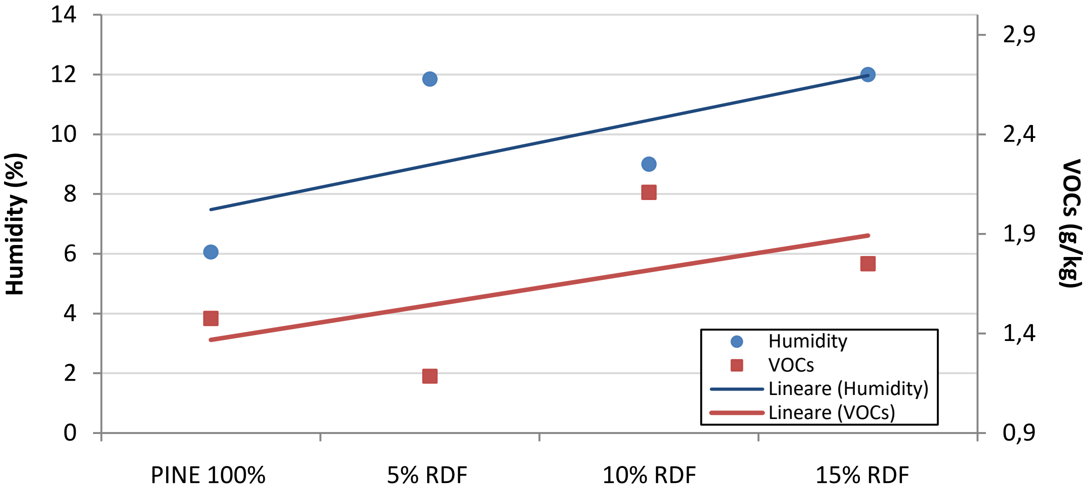


Image 47: Relation between VOCs emissions (g/kg) during the stationary regime and Humidity (%).

A positive dependence between LHV and total VOCs emissions was expected as in the case of the work of Wang et al. (2014). What happens instead is a linear growth of the LHV with increasing percentage of RDF but the same does not happen in the case of VOCs as can be seen from the Image 48. There is a weak correlation between the increase of the LHV and the increase of VOCs in the gaseous emissions.

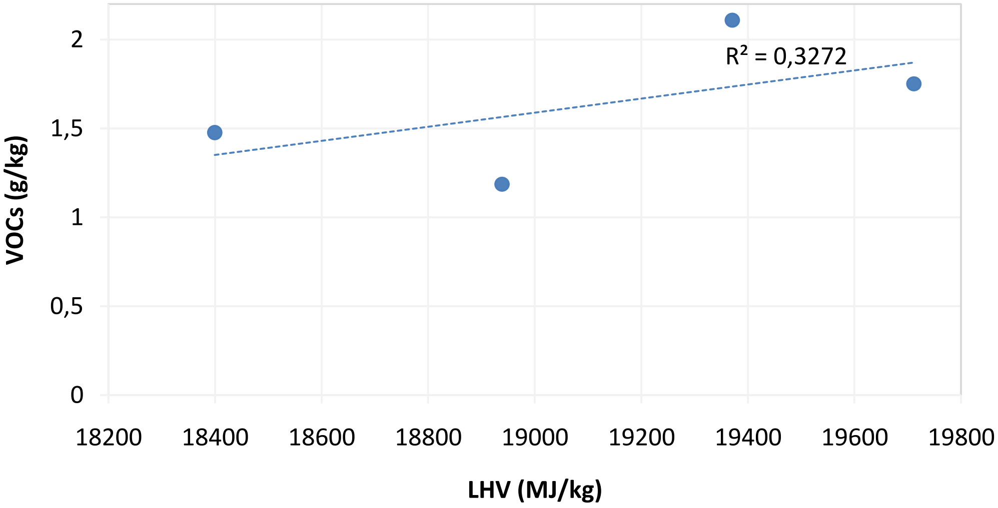


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Image 48: Relation between VOCs emissions (g/kg) during the stationary regime and LHV (MJ/kg).

5. Conclusions

The study of biomass as an alternative fuel to fossil fuels has made much progress in the scientific field. In fact, it can be seen how in recent years there has been an increase in the use of pellet stoves and therefore of the latter as fuels.

At the same time one of the most worrying problems of the twenty-first century is waste and in particular its disposal. The EU has always tried, and still do it today, to invest in recycling, but unfortunately it's very hard to do it with 100% of the waste. A still too large part of waste is disposed of in landfills because it is not recycled and this involves use of space and risk of pollution. This is the reason why it was decided to use the combustion of waste and biomass in the form of pellets for energy production.

In the present research it has been studied the combustion of pellets composed of pine (100%), and different mixes of pine and RDF namely 5% RDF: 95% pine, 10% RDF:90% pine and 15% RDF:85% pine.

One of the most incisive factors that this research has encountered has been humidity, which, as expected, was very low in RDF (about 3%). Therefore, a study on the right amount of humidity for the production of this type of pellets, if necessary, had to be done. Other factors can be decisive for research as pressure, temperature and percentage of RDFs.

For the evaluation of energy efficiency, the lower heating value (LHV) attained were 18399 MJ/kg for the pine and for the pellets formed by the various percentages of RDF (in ascending order of% of RDF) were 18938, 19370 and 19711 MJ/kg.

Perhaps with more in-depth studies It can be said that the use of RDF and pine in pellets can be a good energy solution in terms of thermal efficiency and emissions.

The thermal efficiency of the three types of pellets formed by the different percentages of RDF was very similar (about 50%). Therefore, based on these data and remembering the objective of this work, it has been possible to venture a hypothesis: the pellets produced with 15% of RDF are the most appropriate of the three tested. It is due to the percentage of RDF contained because this pellets have similar thermal efficiency comparing with the other mixtures, but allow diverting larger amounts of wastes from landfills and promoting their valorisation.

About the emissions (CO, CO_2 and NO_x) it can be seen that they are relatively low compared to what is expected from the results. In fact, the pellets composed of RDF have CO_2 values very similar to each other (about 8.6 ppm). The same thing happens in the case of CO emissions where the difference between the different types of pellets is accentuated but not to the point of being able to say that the emissions change substantially. In fact the pellets formed from 100% pine have CO emissions of around 380 ppm while in the case of pellets formed by RDF the CO emissions are on average 470 ppm. The only ones that fall within the normative values are pine pellets. Reviewing all the characteristics of the pellets, it is however possible to draw a result that is not entirely negative. In fact, by conducting a greater number of tests and modifying some factors (for example the humidity content) values could be obtained below the standard.

In the case of NO_x and NO emissions it can be seen an increase as the value of RDF increases as expected.

The VOCs are analysed in the research, in particular during the permanent regime phase, they have gave positive results. In fact, there has been no trend in the various types of pellets as the percentage of RDF varies. From 100% of pine to those formed by 15% of RDF (increasing RDF as a percentage) the VOC values were (g / kg): 1.47, 1.18, 2.10, 1.75. This is probably due to the combustion characteristics. Furthermore unexpectedly, the total VOC emissions have not a strong relation with the LHV.

It should be noted that the pellets mass flow in the case of RDF is lower than that of pine and this is most likely due to the physical characteristics of the fuels. Thus increasing the mass flow of the pellets formed by RDF in the boiler would most likely lead to an increase in thermal efficiency.

It is not to be ignored that, depending on the objectives of Europe, it will be possible to study further percentages of RDF to be added in the pellets in order to eliminate as much waste as possible from landfills. All this will be possible with this specific type of RDF which contains paper, plastic and other materials that raise its heating value. In the event that Europe manages to reach the goal of having 65% recycling in the various countries, RDF will almost certainly not have the same composition as now. There will certainly be less plastic, paper and other recyclable materials that increase the heating value of RDF.

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ANNEX 1- Particle size distribution

Table A.1. 1: Mass retained by sieves of different meshes (decreasing sieve value) for material samples composed of 5% RDFs and 95% pine wood.

	5% RDFs+PINE		
	I SAMPLE	II SAMPLE	III SAMPLE
Sievesm (µm)	**Weight (g)**	**Weight (g)**	**Weight (g)**
4750	0.3	0.3	0.6
4000	0.3	0.6	0.5
3350	0.8	1.2	0.8
2800	1.6	0.6	1.1
2360	2.1	1	2.1
2000	3.6	1.8	3.2
1700	7.5	6.6	6.4
1400	15.8	13.6	15.4
1180	13.9	12.8	13.3
1000	23.6	20.2	23.3
850	8.3	8.4	7.6
710	12.2	11	11.7
600	8.2	7.4	8.7
500	6.5	5.8	6.8
425	5.9	6.6	7.3
355	7.8	3.9	3.2
300	8.8	4.9	5.5
250	4.4	4.9	4.3
212	2.6	3.1	2.7
180	2.8	3.5	3
150	1.8	2.5	1.9
125	3	4.1	2.6
106	2.2	2.7	3
90	1.1	1.8	1.6
<90	11.6	18	12.1

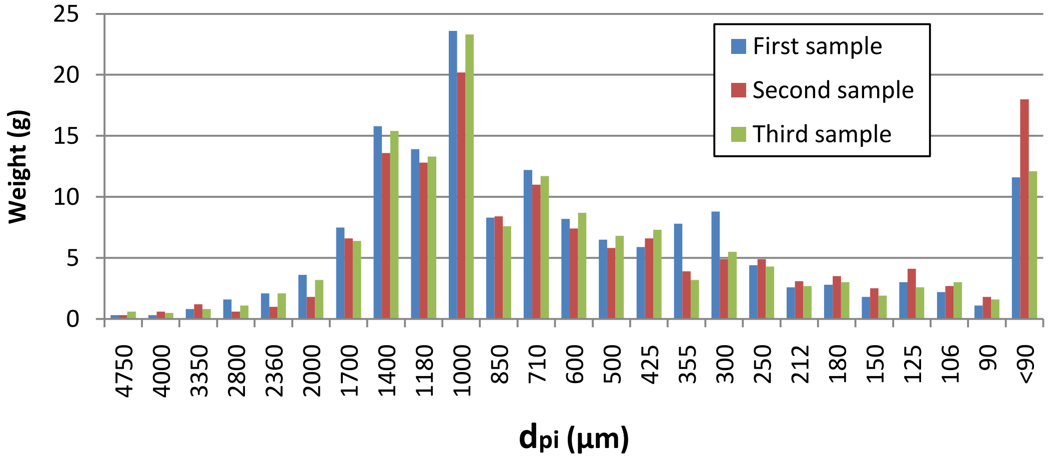


Image A.1. 1: Particle size distribution in sieves of different meshes (5% RDFs + 95% Pine).

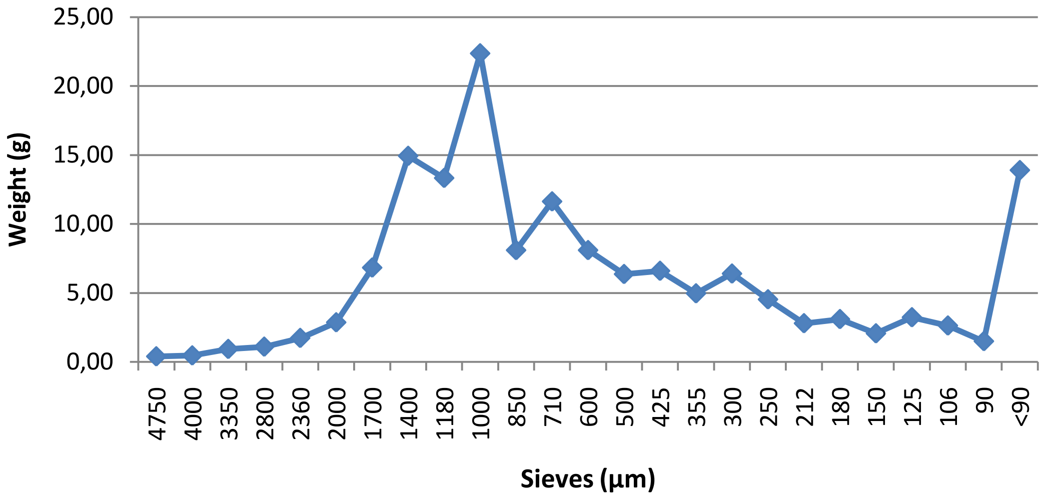


Image A.1. 2: Cumulative curve (5% RDFs + 95% Pine).

Table A.1. 2: Mass retained by sieves of different meshes (decreasing sieve value) for material samples consisting of 10% RDFs and 90% pine wood.

	10% RDF's+PINE		
	I SAMPLE	II SAMPLE	III SAMPLE
Sieves (µm)	**Weight (g)**	**Weight (g)**	**Weight (g)**
4750	0.9	0.7	2.5
4000	0.8	0.7	0.7
3350	1.6	1.7	1.4
2800	2.2	2.2	2.5
2360	3.9	3.3	3.9
2000	5.3	5	5.1
1700	8	8.4	6.6
1400	15	16.9	10.1
1180	13.5	15	8.9
1000	20.6	23	13.8
850	5.9	6.8	4.8
710	9.3	10.5	7.8
600	6.5	7	5.1
500	5	5.3	4.9
425	5.7	6	5.1
355	3	3.4	3.6
300	4.1	3.6	4.2
250	3.8	3.8	3.8
212	2.6	2.2	2.7
180	2.8	2.6	2.6
150	2.2	2	2.7
125	2.7	2.1	2.9
106	2.4	2.1	2.4
90	1.2	1.4	1.2
<90	19.1	13.2	17.8

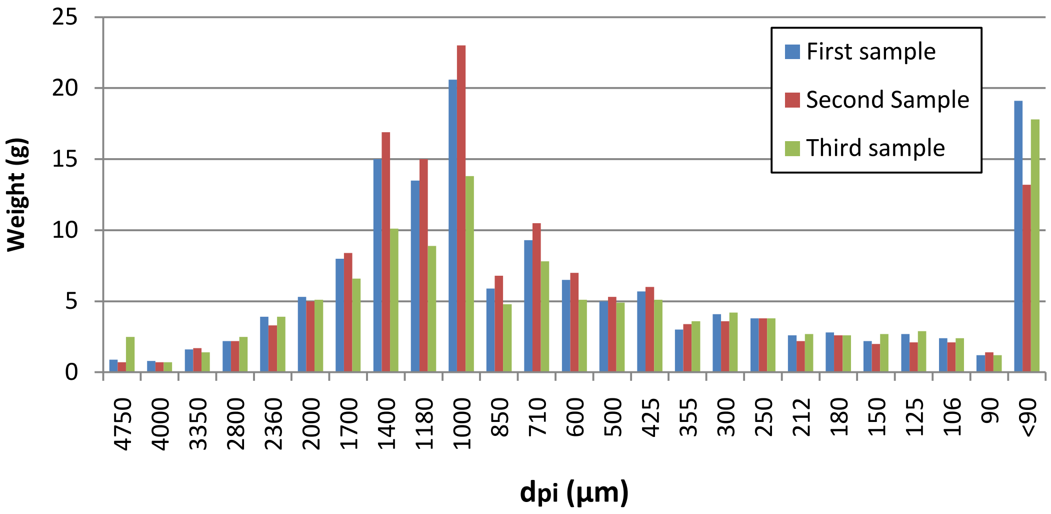


Image A.1. 3: Particle size distribution in sieves of different meshes (10% RDFs + 90% Pine).

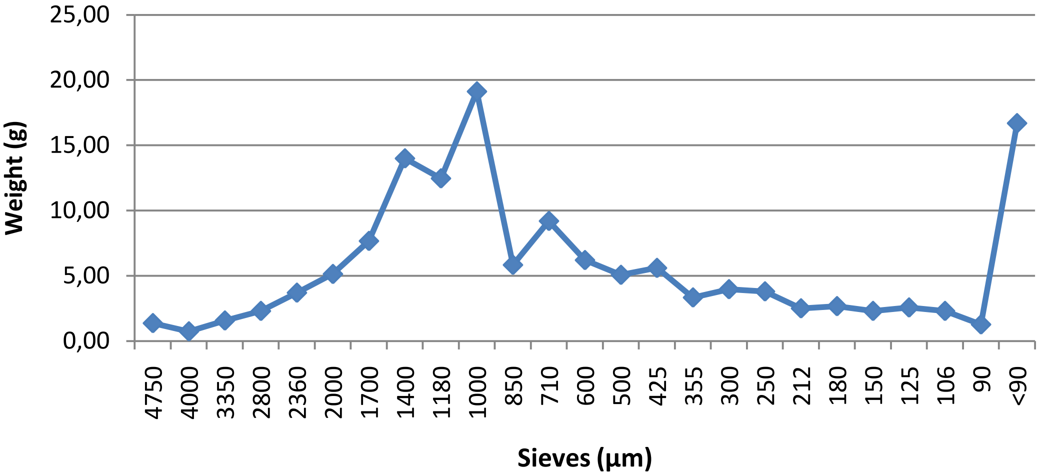


Image A.1. 4: Cumulative curve (10% RDFs + 90% Pine).

Table A.1. 3: Mass retained by sieves of different meshes (decreasing sieve value) for material samples consisting of 15% RDFs and 85% pine wood.

	15% RDF's+PINE		
	I SAMPLE	II SAMPLE	III SAMPLE
Sieves (μm)	**Weight (g)**	**Weight (g)**	**Weight (g)**
4750	0.8	0.5	0.7
4000	0.7	0.6	0.7
3350	1.6	1.3	1.3
2800	2	1.9	1.9
2360	2.6	2.6	2.6
2000	3.7	3.4	3.6
1700	5.2	4.9	5.1
1400	8.8	8.6	8.9
1180	8.4	8.1	8.6
1000	11.9	11.7	12.5
850	4.9	4.9	4.9
710	6.8	7	7
600	4.8	4.8	4.8
500	3.8	4	4
425	4	4.1	4.1
355	2.6	2.7	2.5
300	3.4	3.7	3.4
250	2.1	2.2	2.1
212	1.8	2	1.7
180	2.3	2.5	2.2
150	1.6	1.7	1.5
125	1.7	1.9	1.7
106	1.8	2.3	1.5
90	1	1	1.1
<90	11.1	10.4	10.2

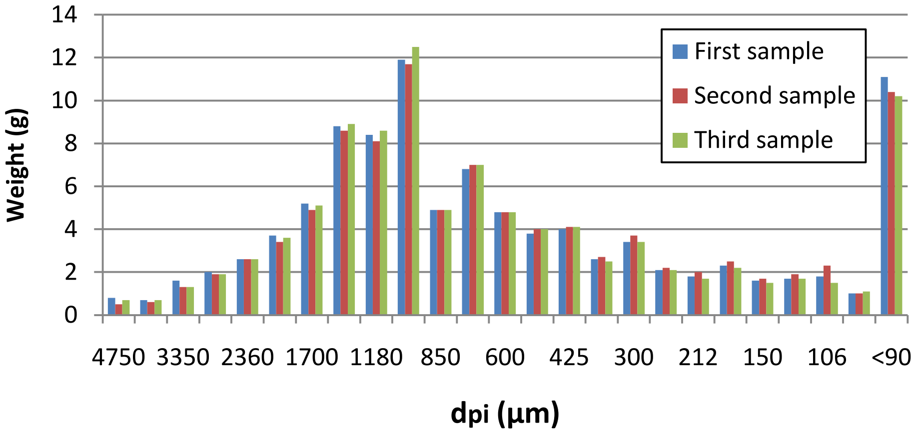


Image A.1. 5: Particle size distribution in sieves of different meshes (15% RDFs + 85% Pine).

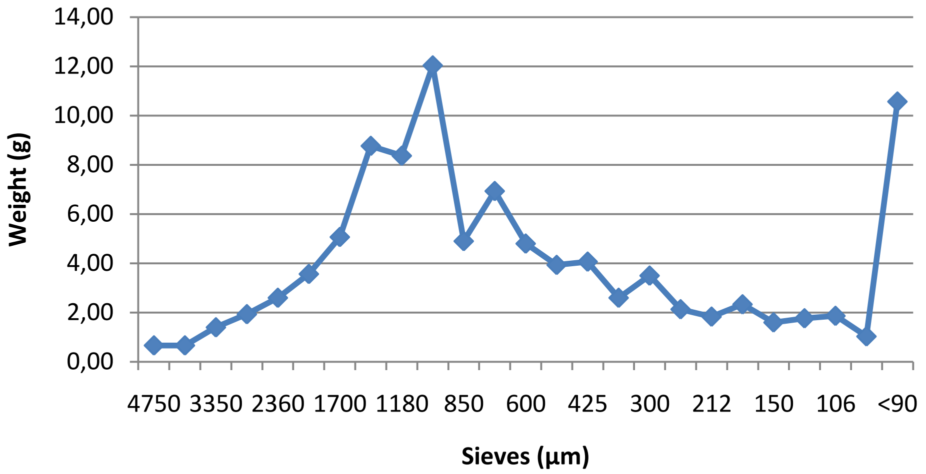
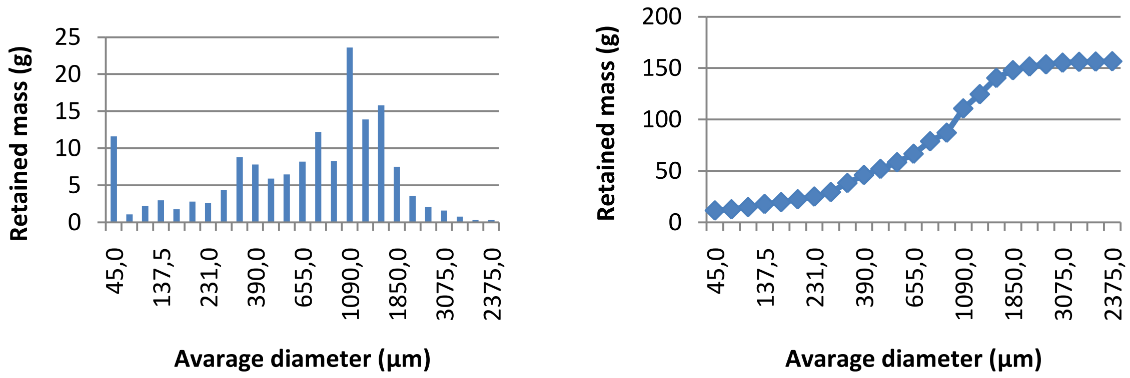
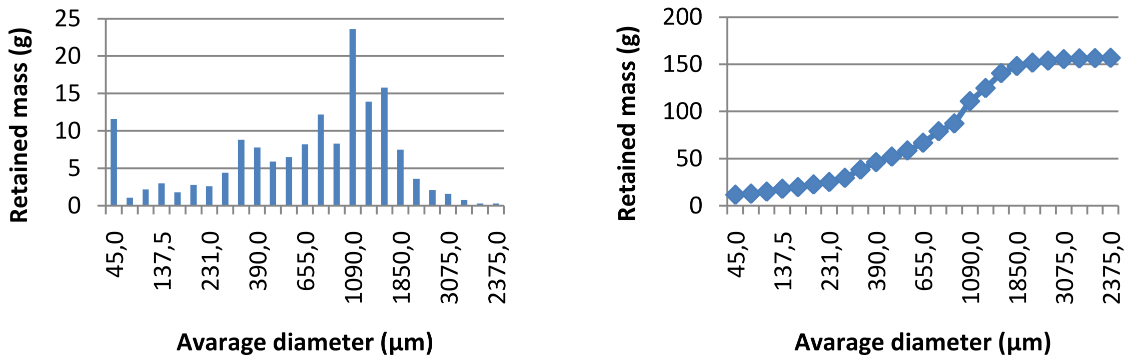


Image A.1. 6: Cumulative curve (15% RDFs + 85% pine).



a) b)

Image A.1. 7: a) Distribution of the average mass retained as a function of the average diameter of the particles retained by the sieves; b) Cumulative curve of the average mass retained as a function of the average diameter of the particles retained by the sieves- I sample containing 5% of RDFs.



a) b)

Image A.1. 8: a) Distribution of the average mass retained as a function of the average diameter of the particles retained by the sieves; b) Cumulative curve of the average mass retained as a function of the average diameter of the particles retained by the sieves - II sample containing 5% of RDFs.

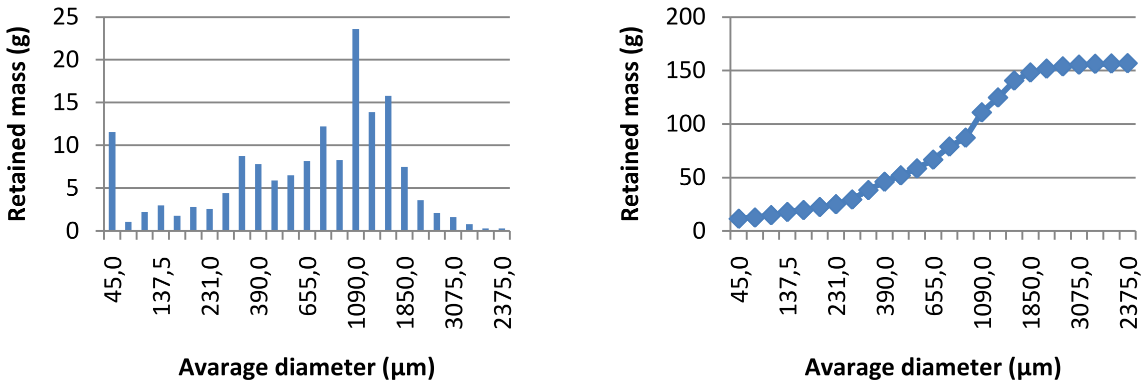
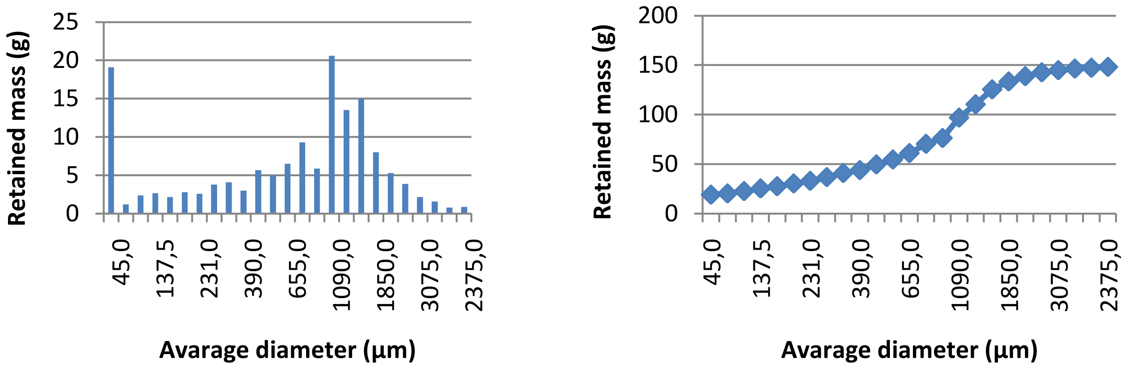
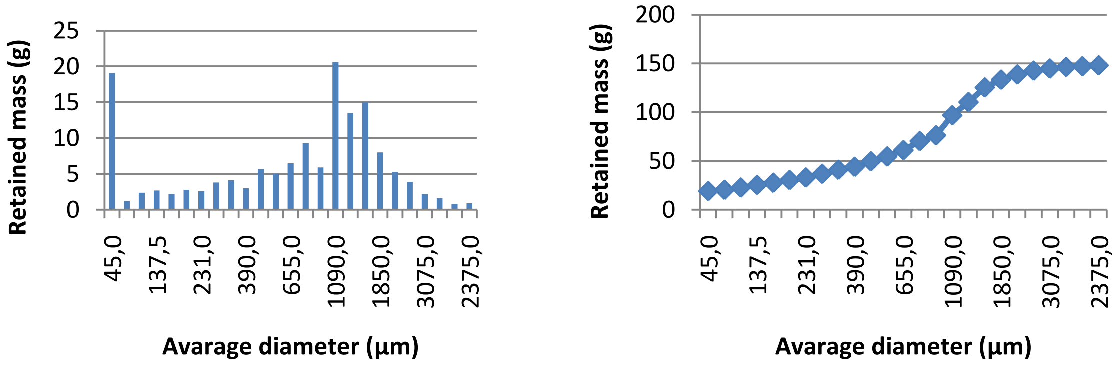


Image A.1. 9: a) Distribution of the average mass retained as a function of the average diameter of the particles retained by the sieves; b) Cumulative curve of the average mass retained as a function of the average diameter of the particles retained by the sieves - III sample containing 5% of RDFs.



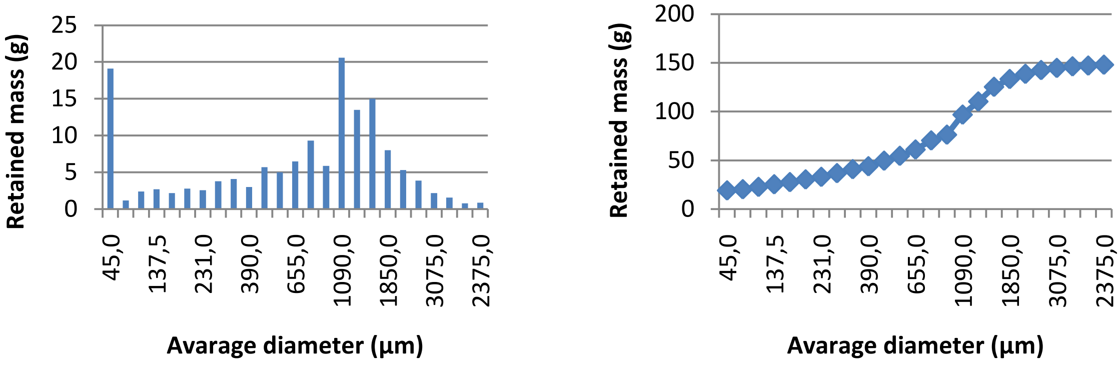
a) b)

Image A.1. 10: a) Distribution of the average mass retained as a function of the average diameter of the particles retained by the sieves; b) Cumulative curve of the average mass retained as a function of the average diameter of the particles retained by the sieves - I sample containing 10% of RDFs.



a) b)

Image A.1. 11: a) Distribution of the average mass retained as a function of the average diameter of the particles retained by the sieves; b) Cumulative curve of the average mass retained as a function of the average diameter of the particles retained by the sieves - II sample containing 10% of RDFs.



a) b)

Image A.1. 12: a) Distribution of the average mass retained as a function of the average diameter of the particles retained by the sieves; b) Cumulative curve of the average mass retained as a function of the average diameter of the particles retained by the sieves - III sample containing 10% of RDFs.

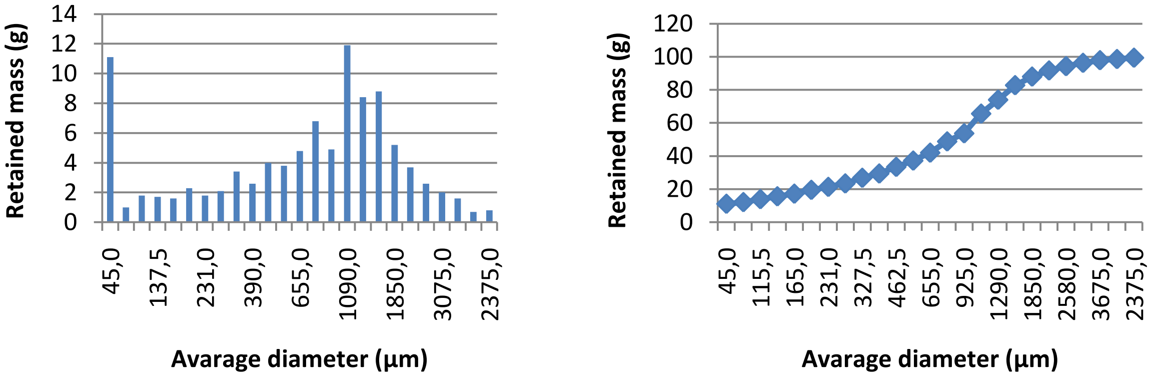
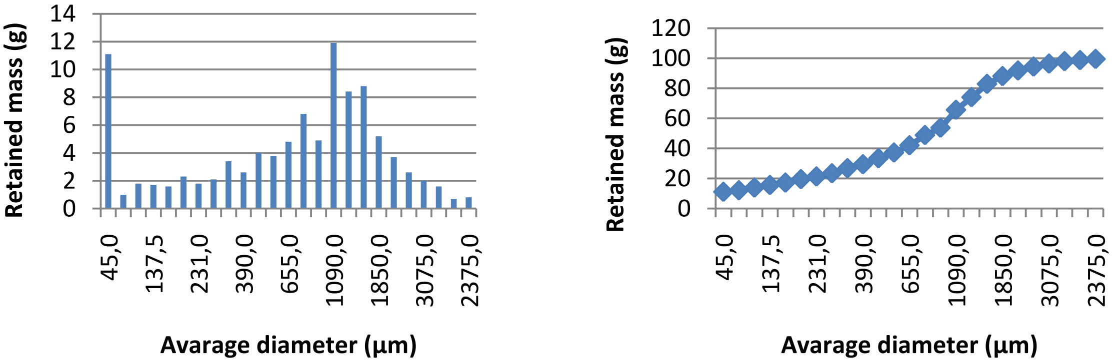
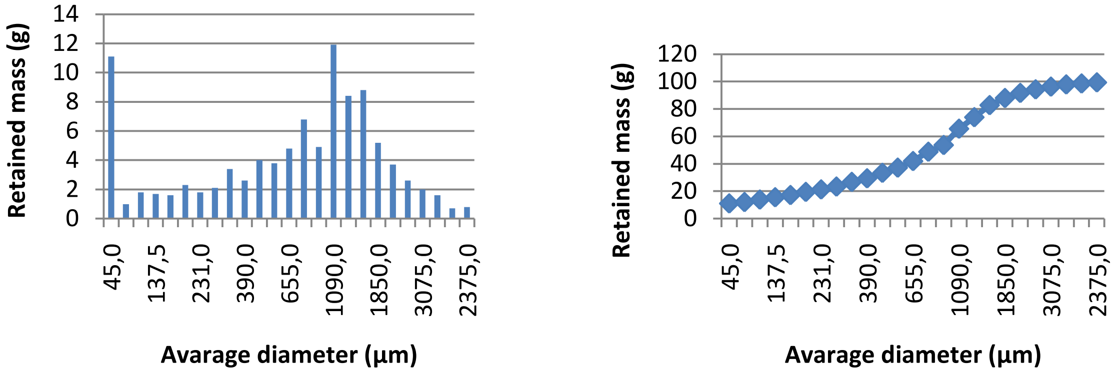


Image A.1. 13: a) Distribution of the average mass retained as a function of the average diameter of the particles retained by the sieves; b) Cumulative curve of the average mass retained as a function of the average diameter of the particles retained by the sieves - I sample containing 15% of RDFs.



a) b)

Image A.1. 14 a) Distribution of the average mass retained as a function of the average diameter of the particles retained by the sieves; b) Cumulative curve of the average mass retained as a function of the average diameter of the particles retained by the sieves - II sample containing 15% of RDFs.



a) b)

Image A.1. 15: a) Distribution of the average mass retained as a function of the average diameter of the particles retained by the sieves; b) Cumulative curve of the average mass retained as a function of the average diameter of the particles retained by the sieves - III sample containing 15% of RDFs.

ANNEX 2- Diameter, length and mass (Volume and density)

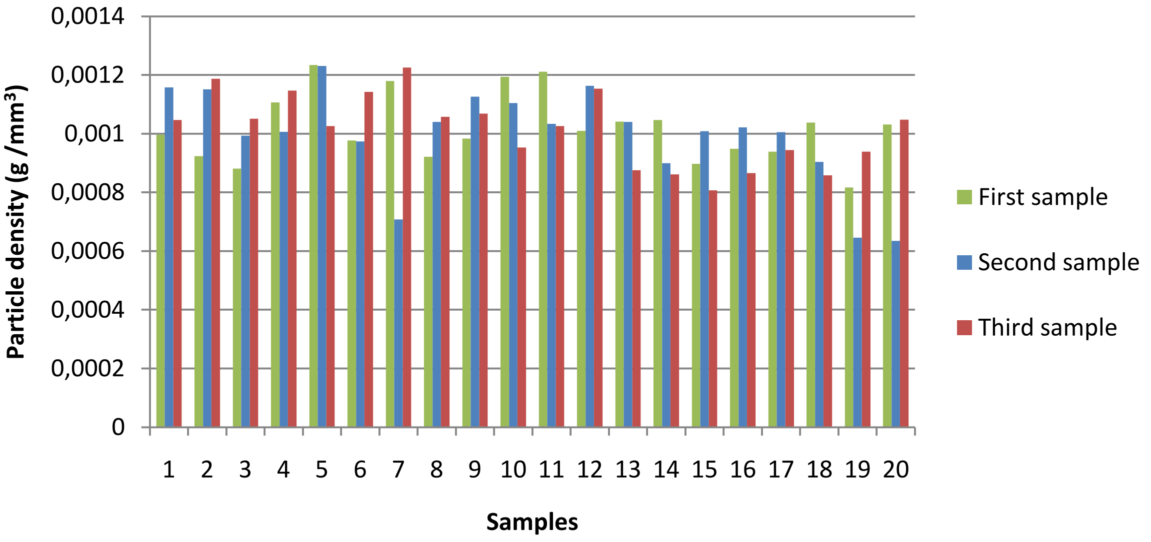


Image A.2. 1: Values of diameter, length, mass, volume and particle density of 20 pellets made from 100% pine wood.

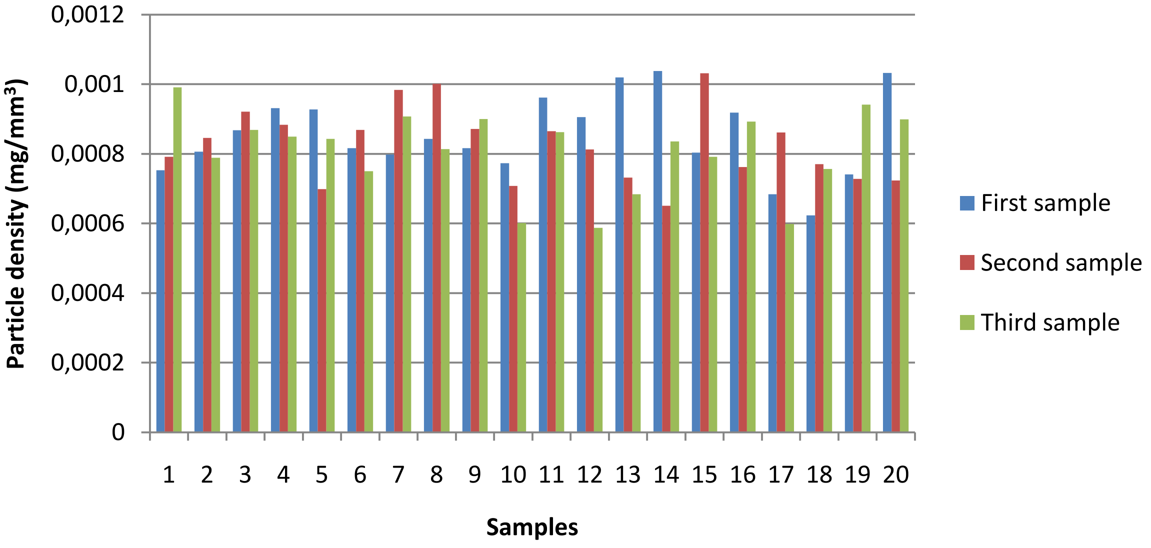


Image A.2. 2: Values of diameter, length, mass, volume and particle density of 20 pellets composed of 5% RDFs + 95% pine wood.

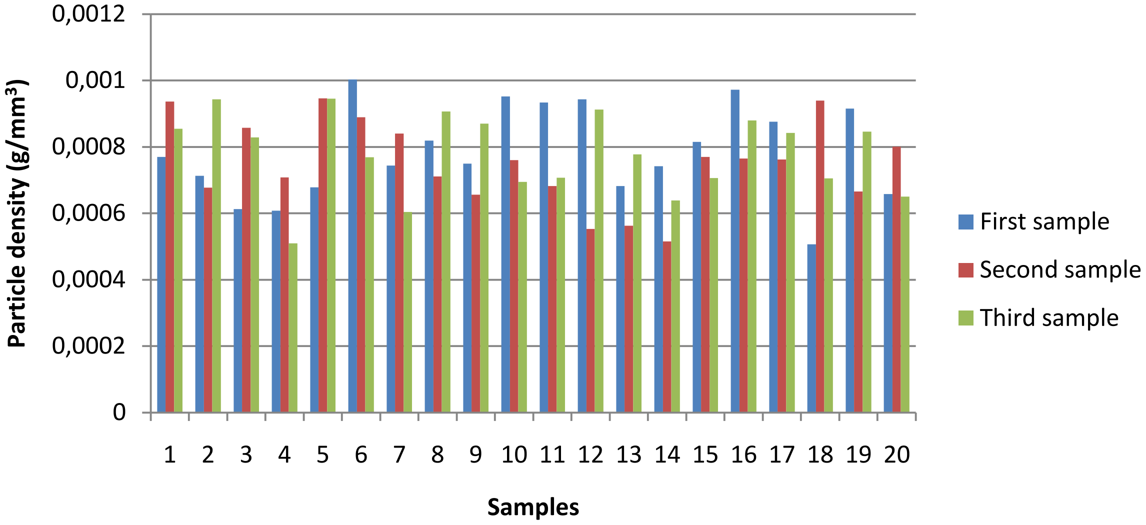


Image A.2. 3: Values of diameter, length, mass, volume and density of 20 pellets composed of 10% RDFs + 90% pine wood.

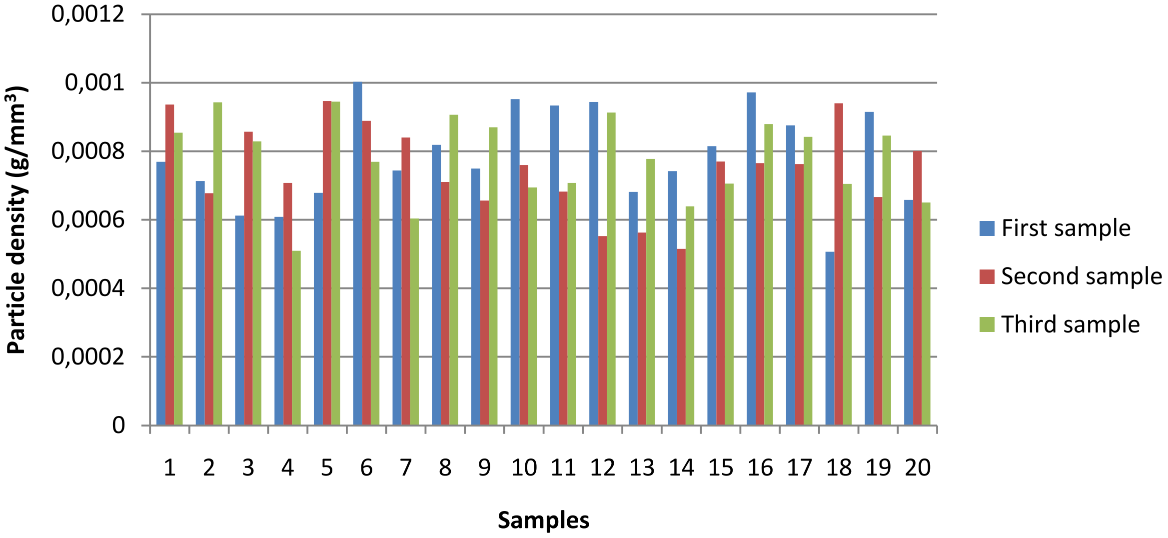


Image A.2. 4: Values of diameter, length, mass, volume and density of 20 pellets composed of 15% RDFs + 85% pine wood.

ANNEX 3- Burning tests results

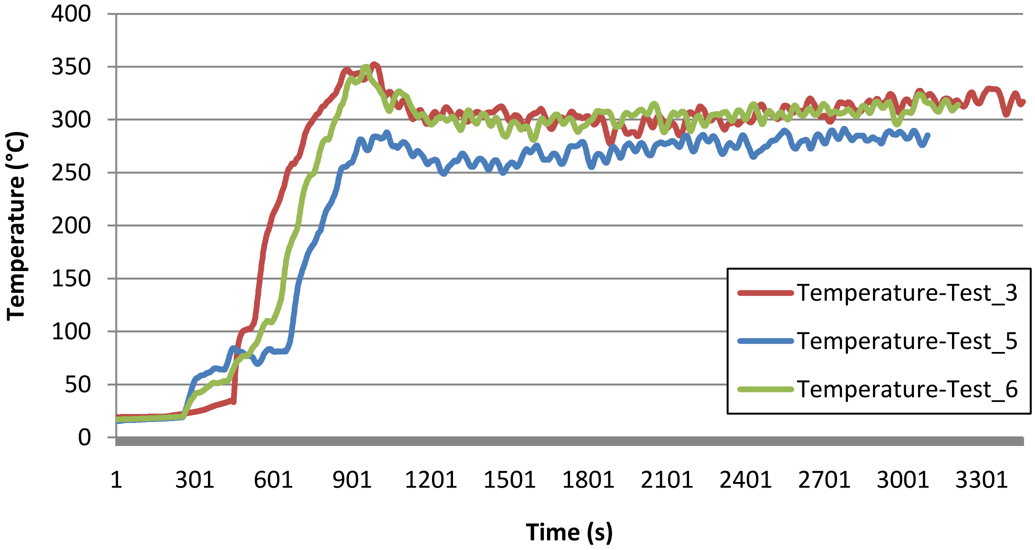


Image A.3. 1: Gases temperature evolution during the combustion of pine pellets (100%).

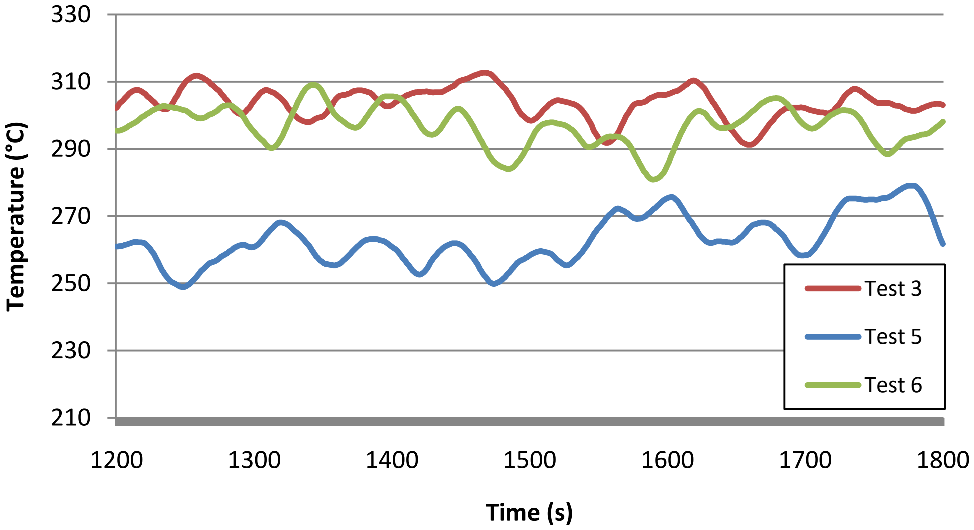


Image A.3. 2: Gases temperature evolution during the combustion of Pino pellets (100%) in the 10 minute stationary regime (1200 s-1800 s).

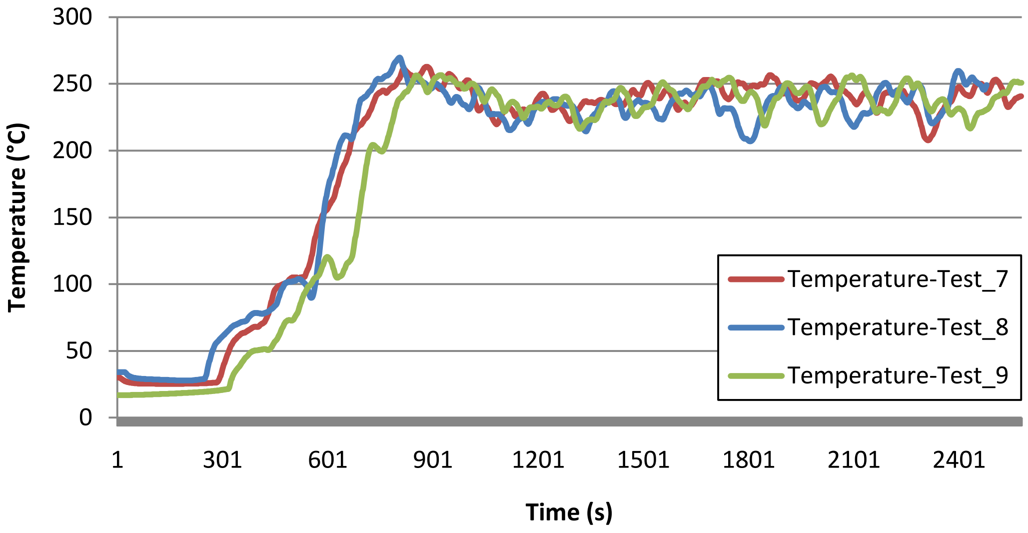


Image A.3. 3: Gases temperature evolution during the combustion of pine pellets of RDF (5%) + Pine (95%).

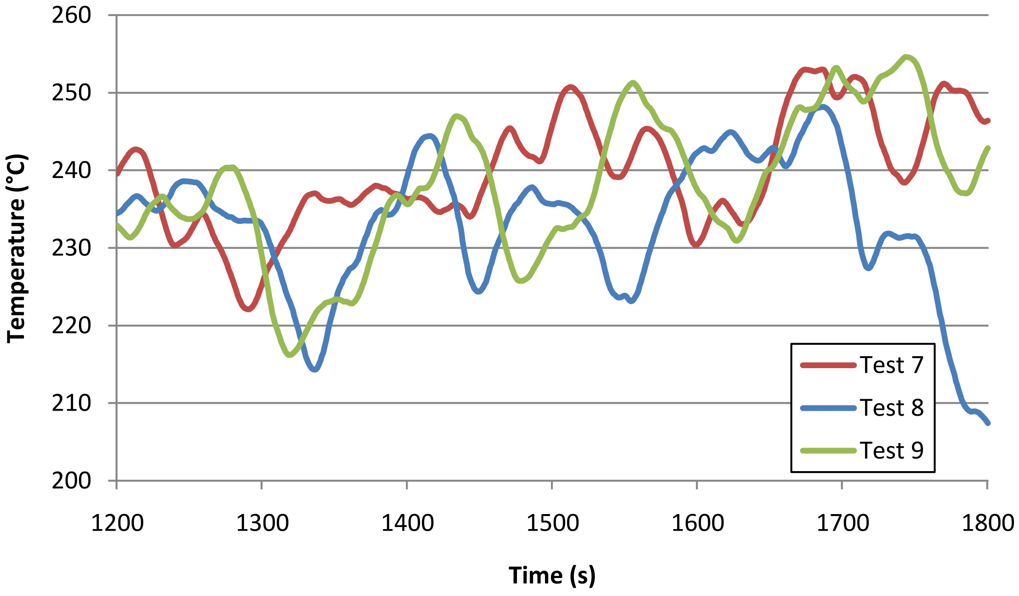


Image A.3. 4: Gases temperature evolution during the combustion of RDF pellets (5%) + Pine (95%) in the 10 minute stationary regime (1200 s-1800 s).

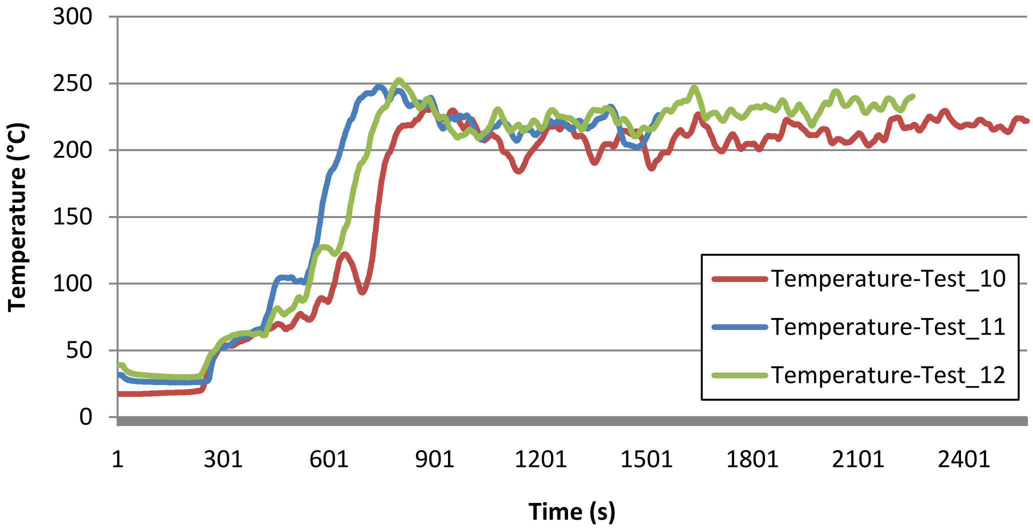


Image A.3. 5: Gases temperature evolution during the combustion of pine pellets of RDF (10%) + Pine (90%).

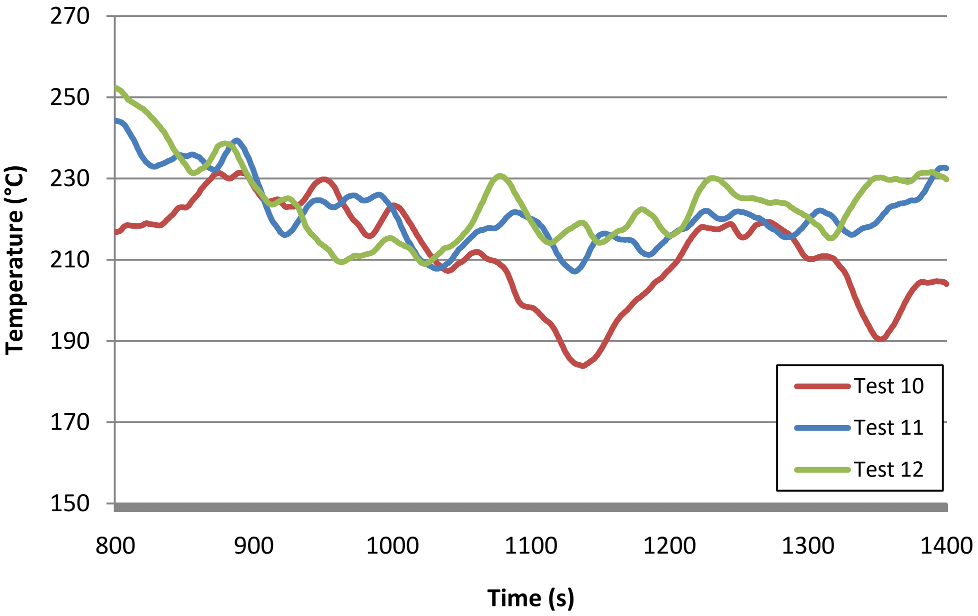


Image A.3. 6: Gases temperature evolution during the combustion of RDF pellets (10%) + Pine (90%) in the stationary regime 10 minutes (800 s-1400 s).

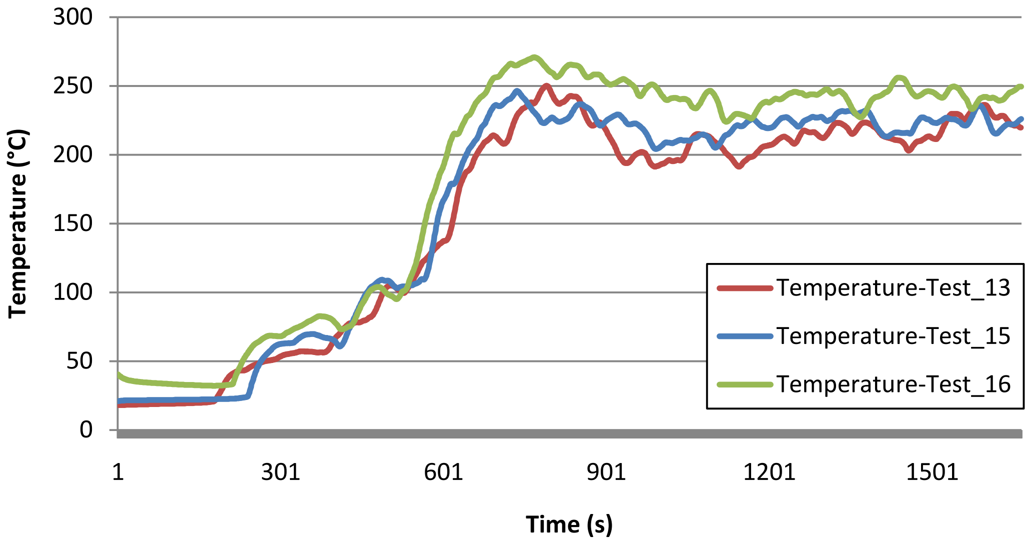


Image A.3. 7: Gases temperature evolution during the combustion of pine pellets of RDF (15%) + Pine (85%).

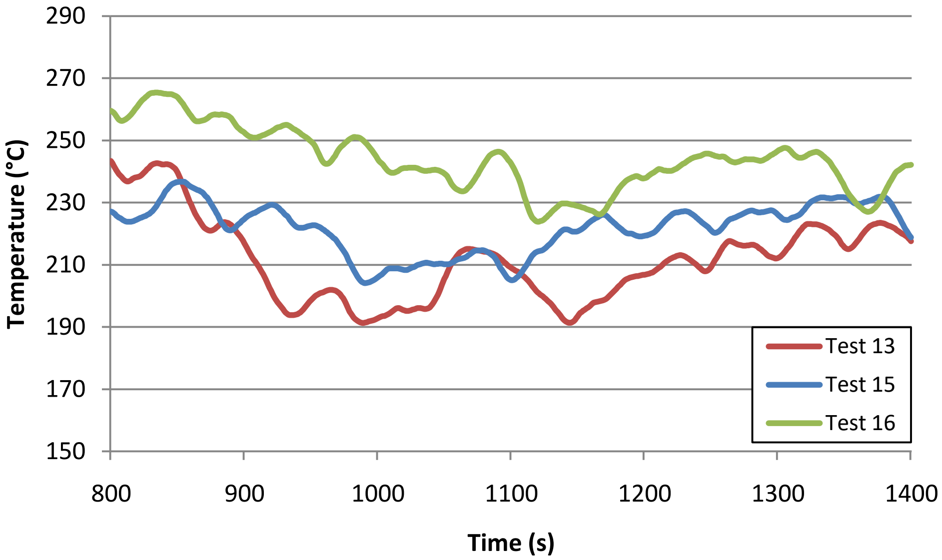


Image A.3. 8: Gases temperature evolution during the combustion of RDF pellets (15%) + Pine (85%) in the 10 minute stationary regime (800 s-1600 s).

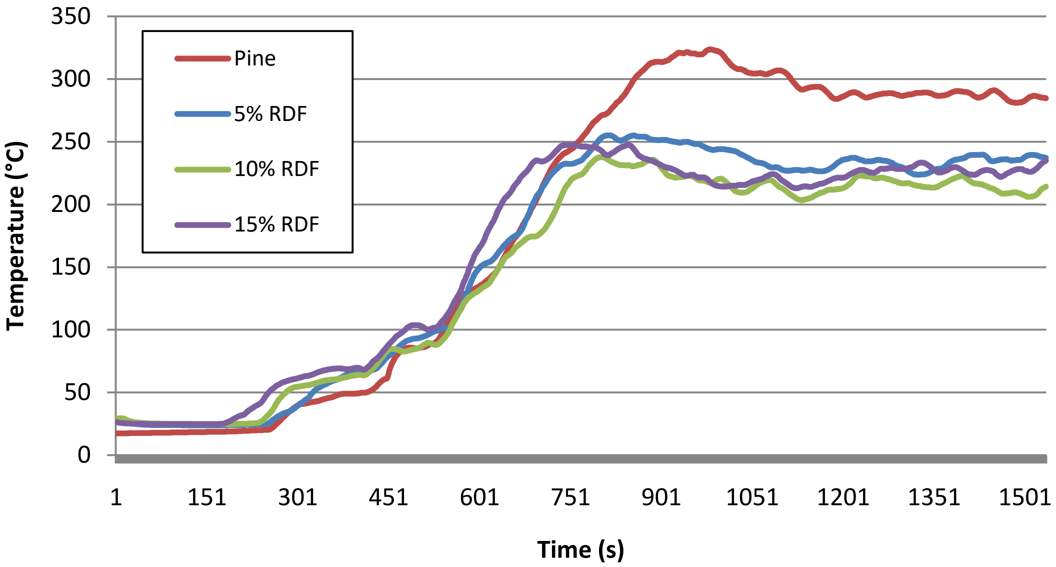
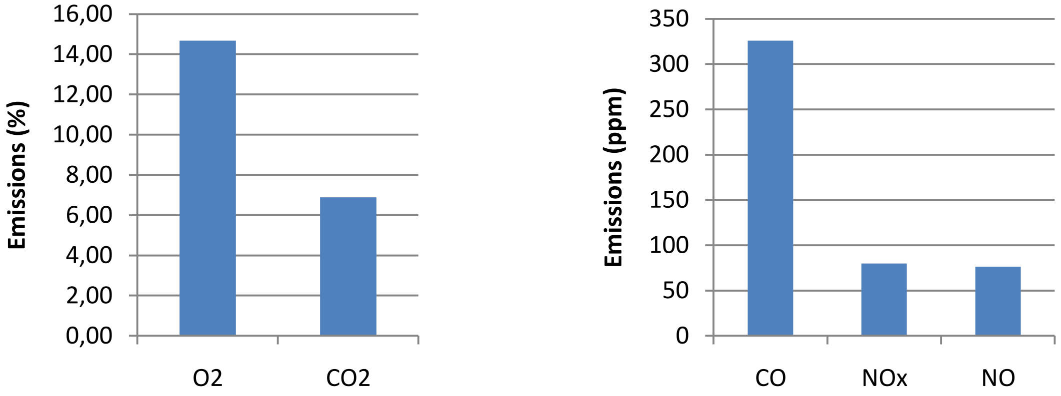


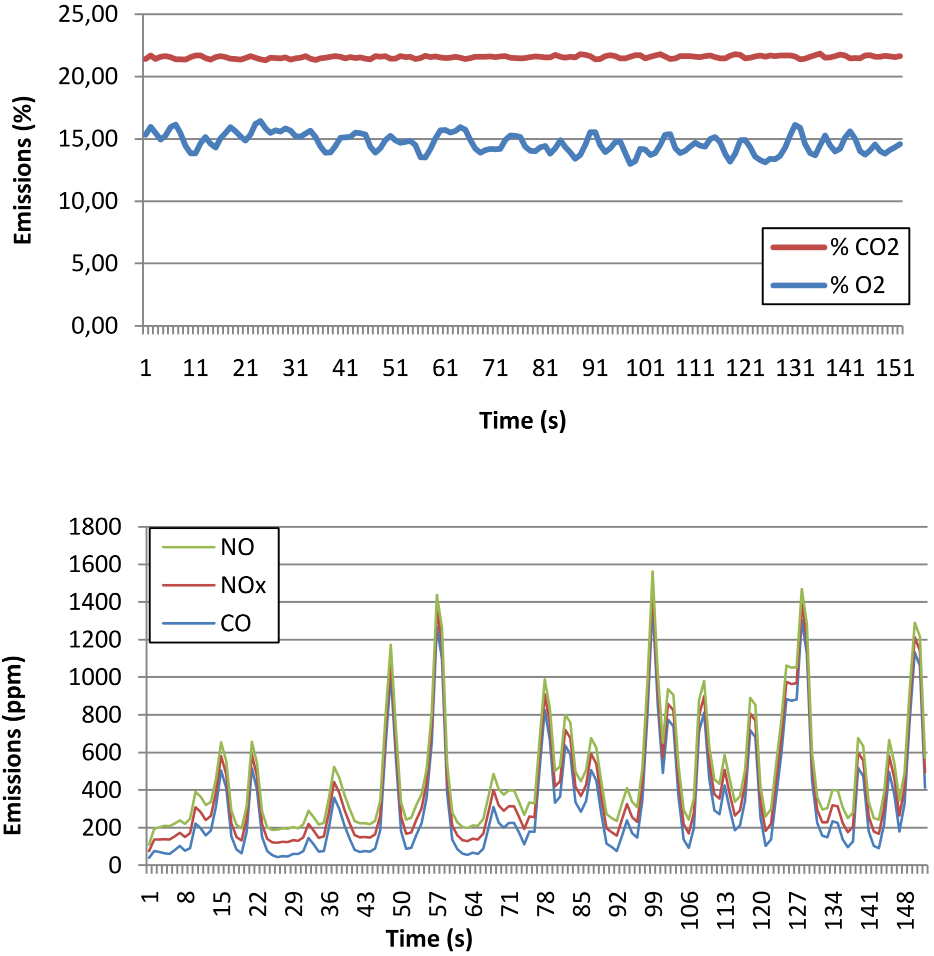
Image A.3. 9: Gases temperature evolution during the combustion of the four types of pellets.

ANNEX 4- Gaseous emissions



a) b)

Image A.4. 1: a) Concentration of O_2 and CO_2 during the combustion of pine pellets (100% pine-test_3);b) Concentration of CO, NO_x and NO during the combustion of pine pellets (100% pine-test_3).



a)

b)

Image A.4. 2: a) Trend of O_2 and CO_2 emissions during the combustion of pine pellets (100% pine-test_3);b) Trend of CO, NO_x and NO emissions during the combustion of pine pellets (100% pine-test_3).

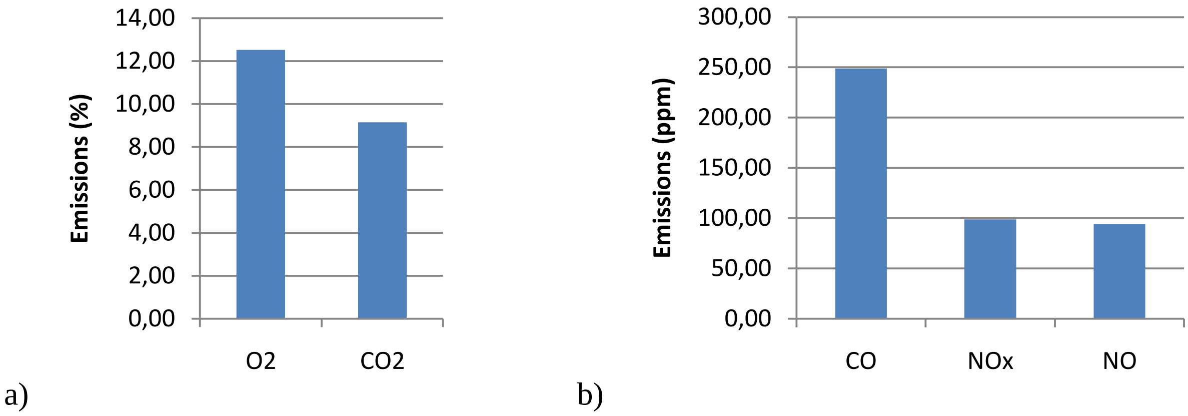


Image A.4. 3: a) Concentration of O_2 and CO_2 during tests_5 of combustion of pine pellets (100% pine); b) Concentration of CO, NO_x and NO during the combustion of pine pellets (100% pine).

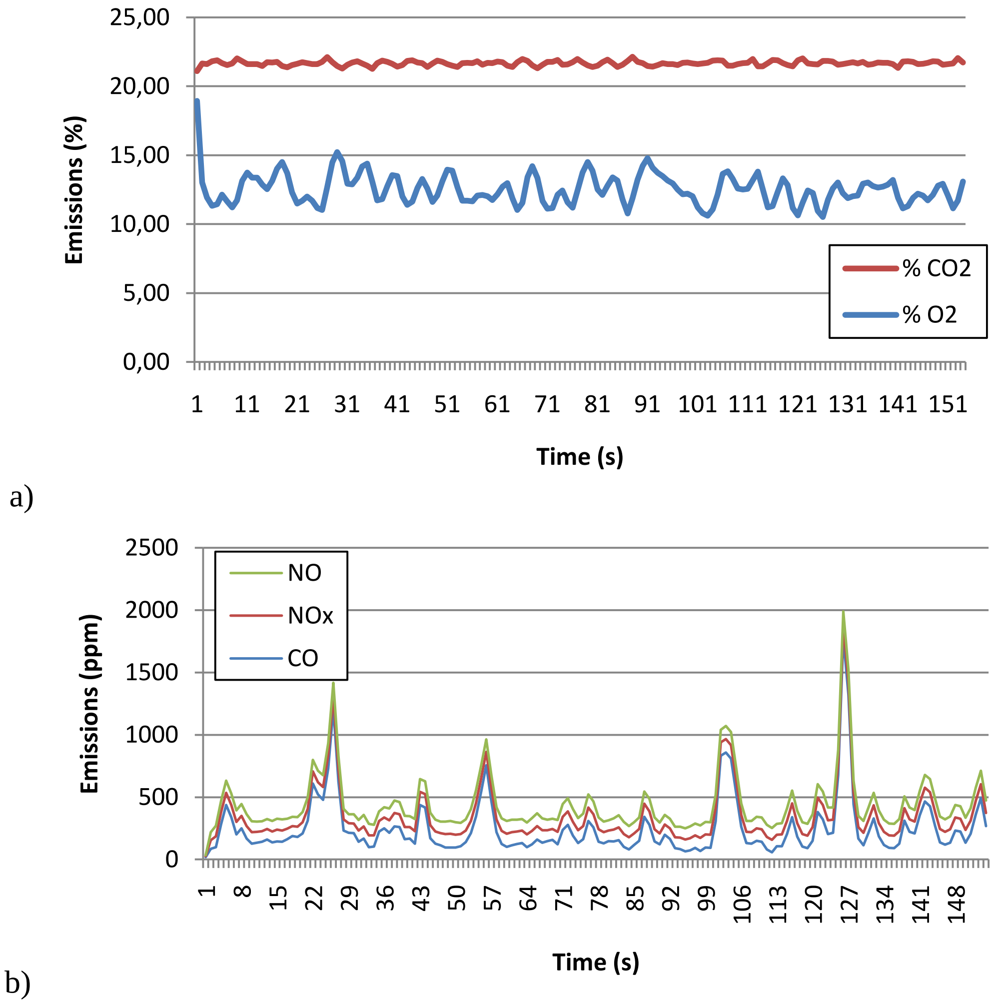
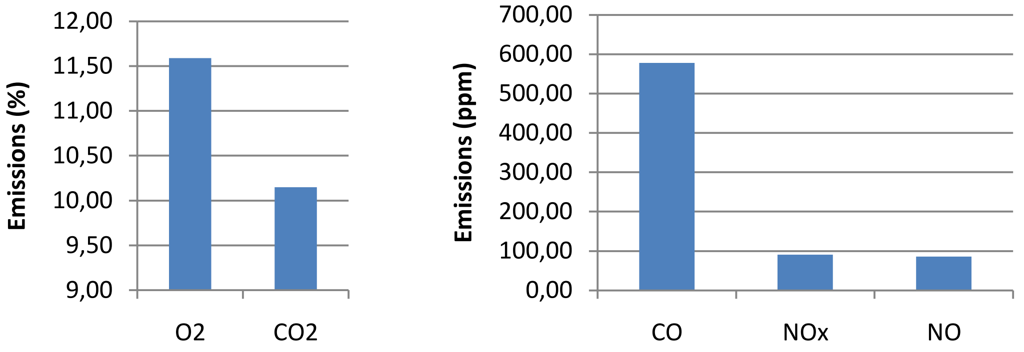
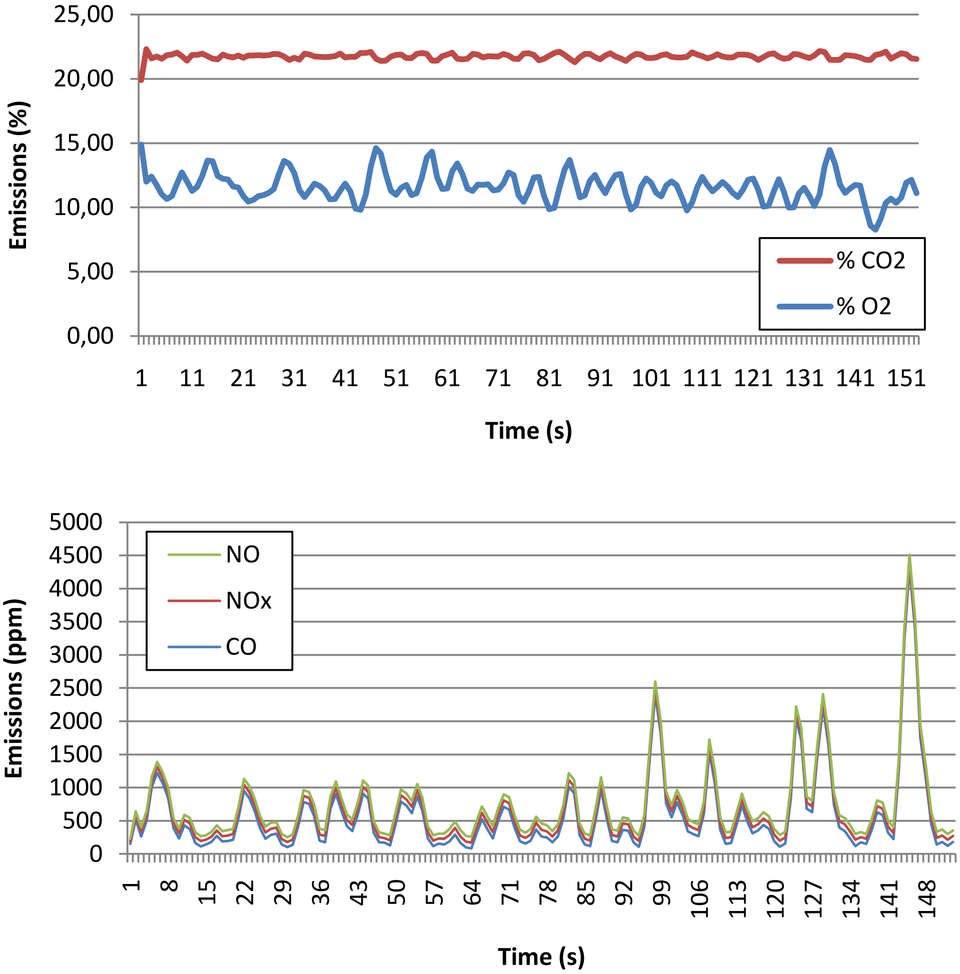


Image A.4. 4: a) Trend of O_2 and CO_2 emissions during the combustion of pine pellets (100% pine-test_5);b) Trend of CO, NO_x and NO emissions during the combustion of pine pellets (100% pine-test_5).



a) b)

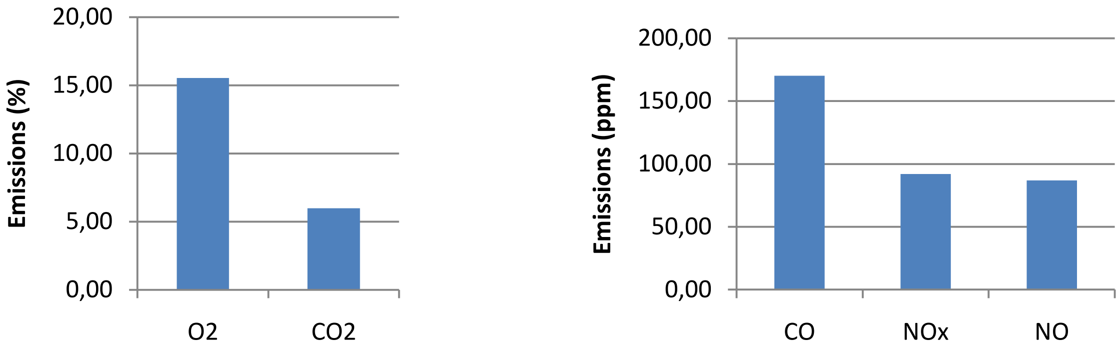
Image A.4. 5: a) Concentration of O_2 and CO_2 during the combustion of pine pellets (100% pine-test_6);b) Concentration of CO, NO_x and NO during the combustion of pine pellets (100% pine-test_6).



a)

b)

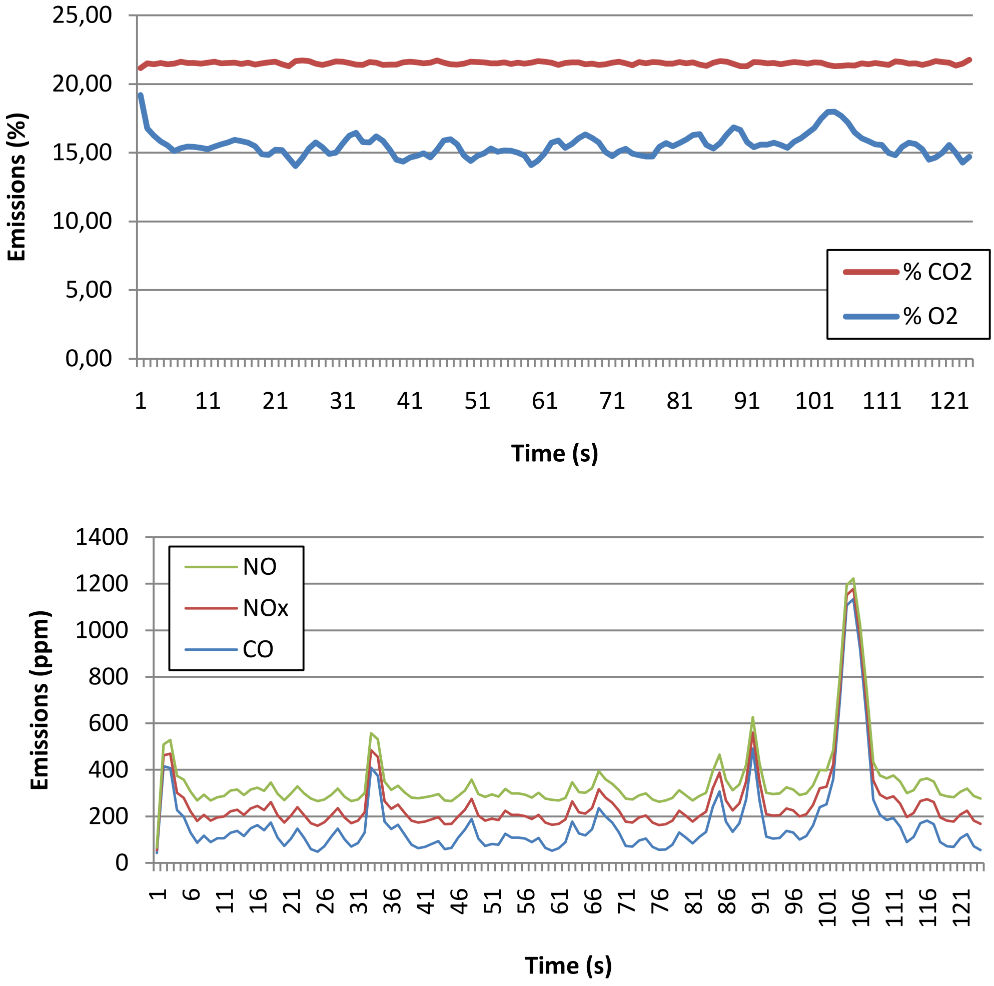
Image A.4. 6: a) Trend of O_2 and CO_2 emissions during the combustion of pine pellets (100% pine-test_6);b) Trend of CO, NO_x and NO emissions during the combustion of pine pellets (100% pine-test_6).



a)

b)

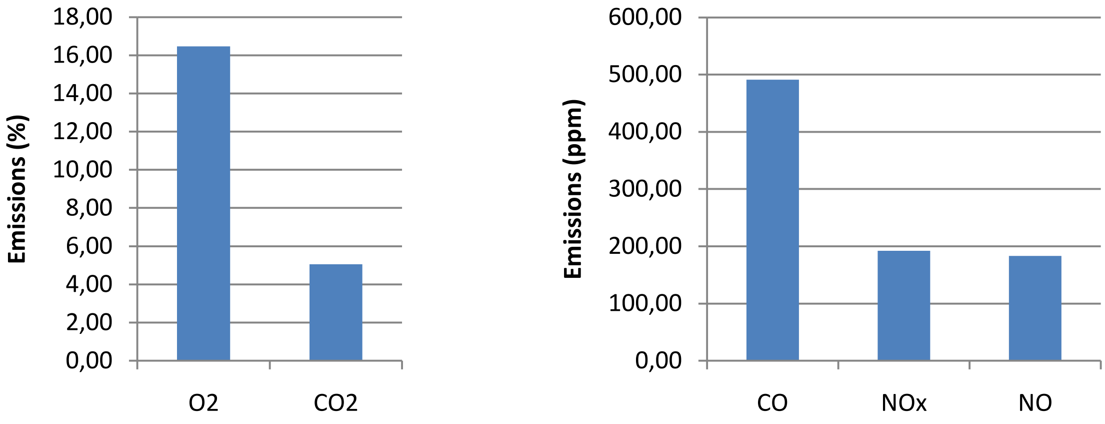
Image A.4. 7: a) Concentration of O_2 and CO_2 during the combustion of pine pellets (5%RDF-test_7);b) Concentration of CO, NO_x and NO during the combustion of pine pellets (5% RDFs -test_7).



a)

b)

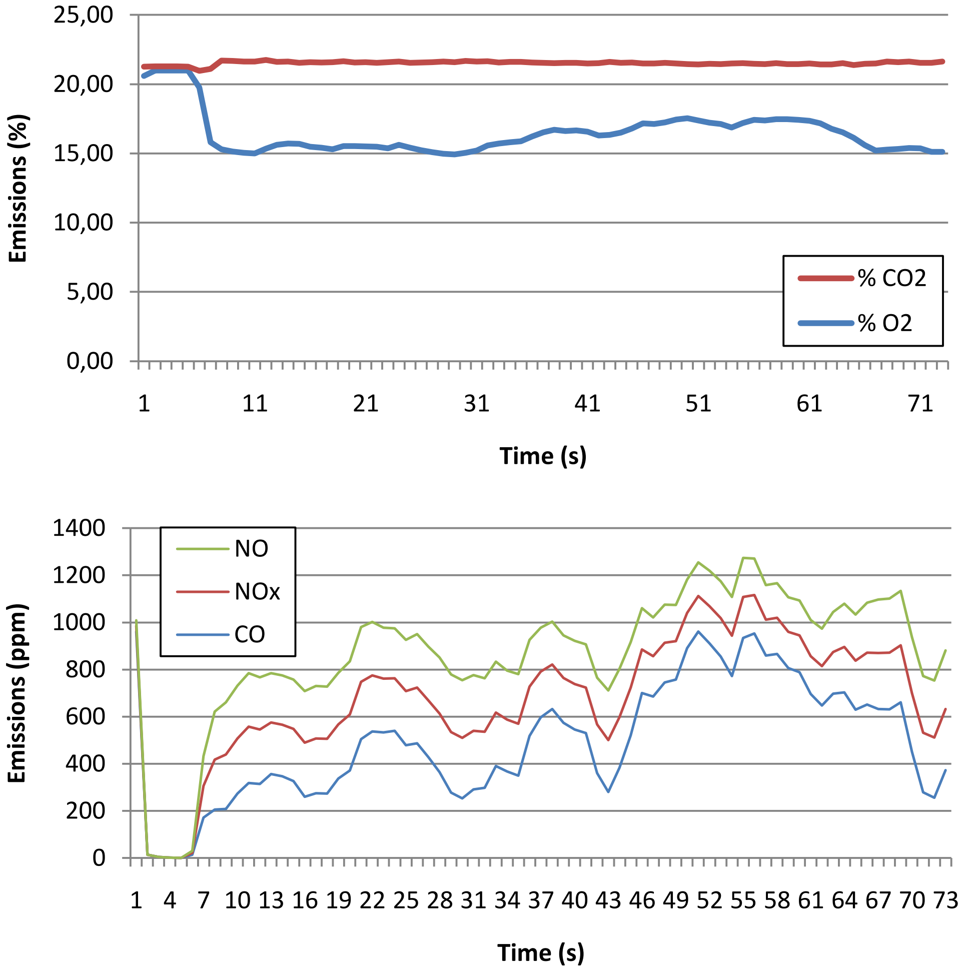
Image A.4. 8: a) Trend of O_2 and CO_2 emissions during the combustion of pine pellets (5%RDF -test_7);b) Trend of CO, NO_x and NO emissions during the combustion of pine pellets (5% RDFs -test_7).



a)

b)

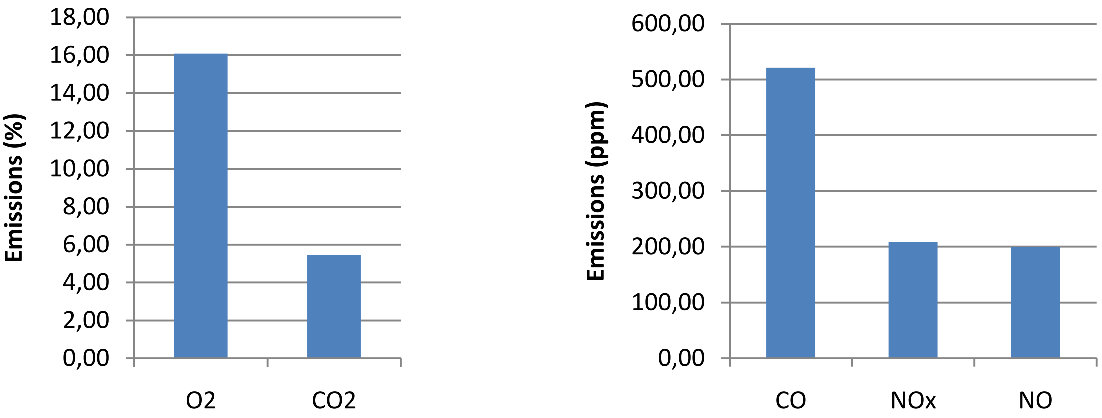
Image A.4. 9: a) Concentration of O_2 and CO_2 during the combustion of pine pellets (5%RDF test_8);b) Concentration of CO, NO_x and NO during the combustion of pine pellets (5% RDFs -test_8).



a)

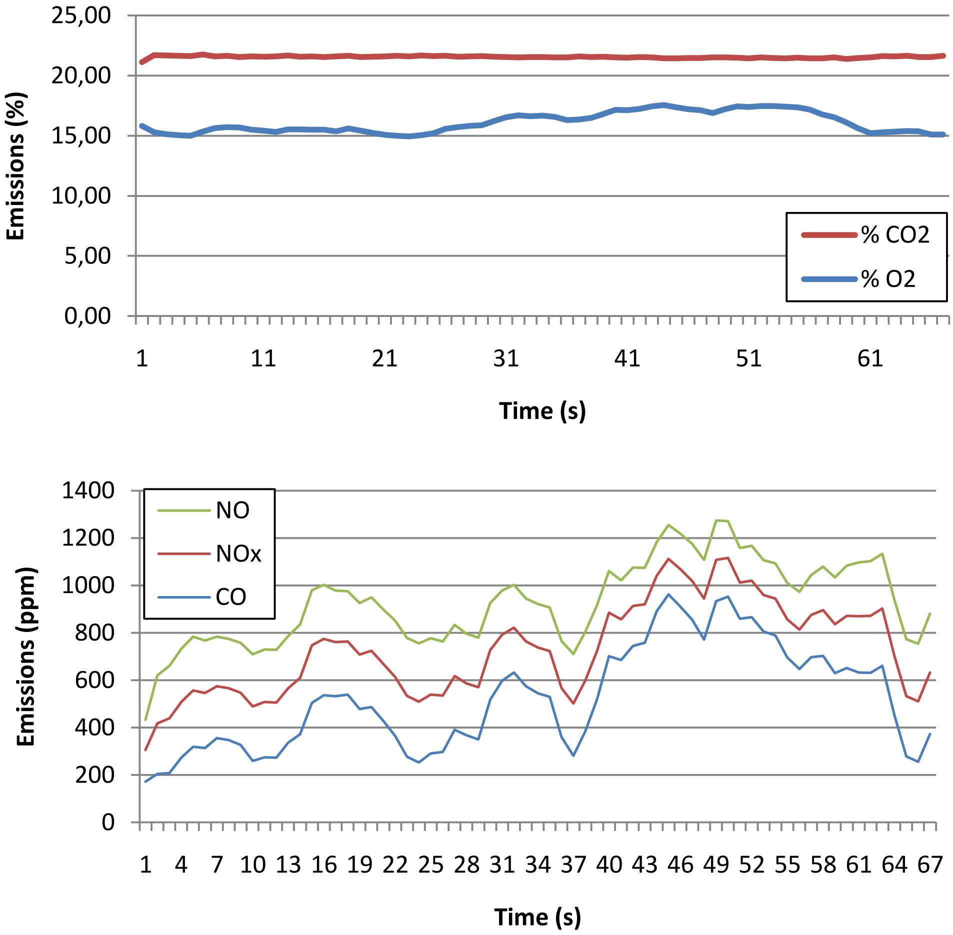
b)

Image A.4. 10: a) Trend of O_2 and CO_2 emissions during the combustion of pine pellets (5%RDF -test_8);b) Trend of CO, NO_x and NO emissions during the combustion of pine pellets (5% RDFs -test_8).



a) b)

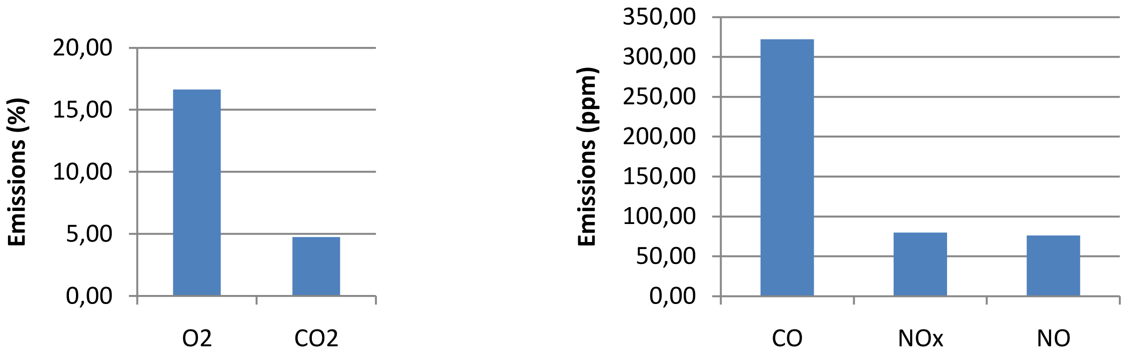
Image A.4. 11: a) Concentration of O_2 and CO_2 during the combustion of pine pellets (5%RDF test_9);b) Concentration of CO, NO_x and NO during the combustion of pine pellets (5% RDFs -test_9).



a)

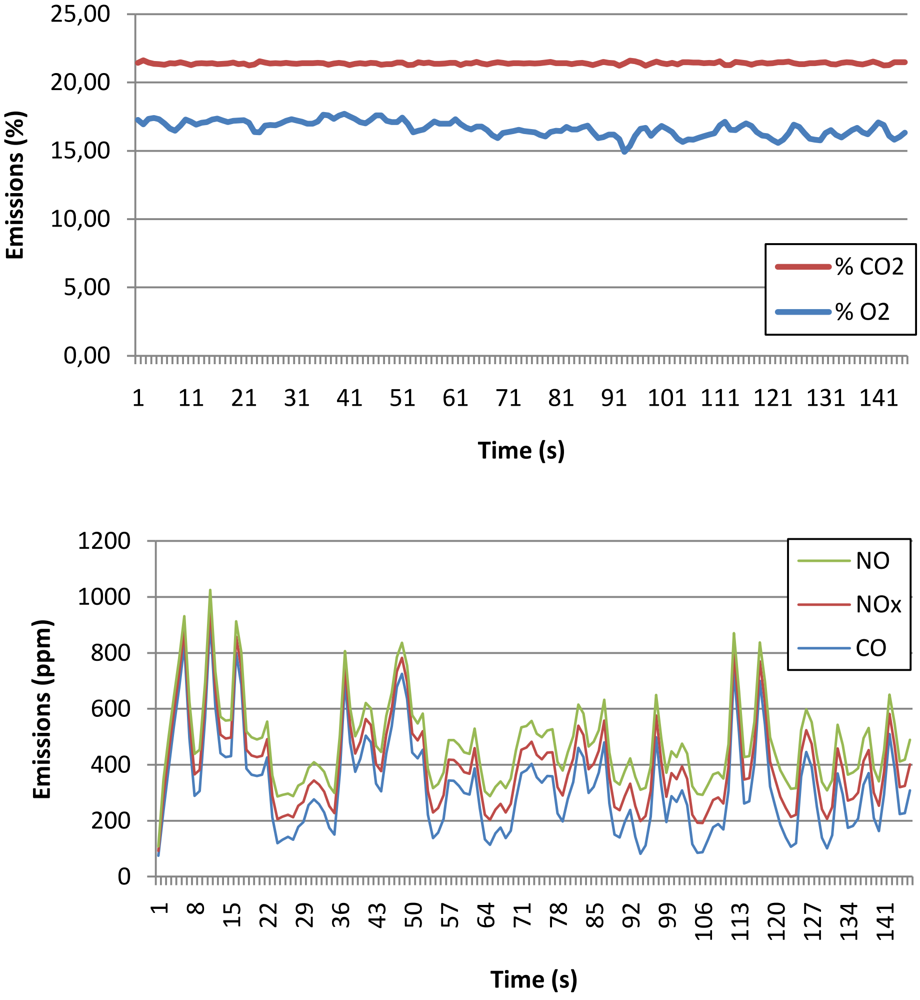
b)

Image A.4. 12: a) Trend of O_2 and CO_2 emissions during the combustion of pine pellets (5%RDF -test_9);b) Trend of CO, NO_x and NO emissions during the combustion of pine pellets (5% RDFs -test_9).



a) b)

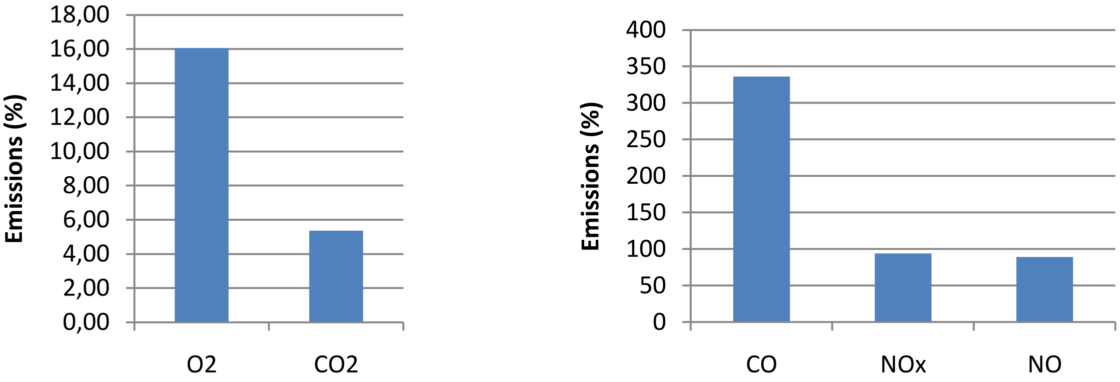
Image A.4. 13: a) Concentration of O_2 and CO_2 during the combustion of pine pellets (10%RDF test_10);b) Concentration of CO, NO_x and NO during the combustion of pine pellets (10% RDFs -test_10).



a)

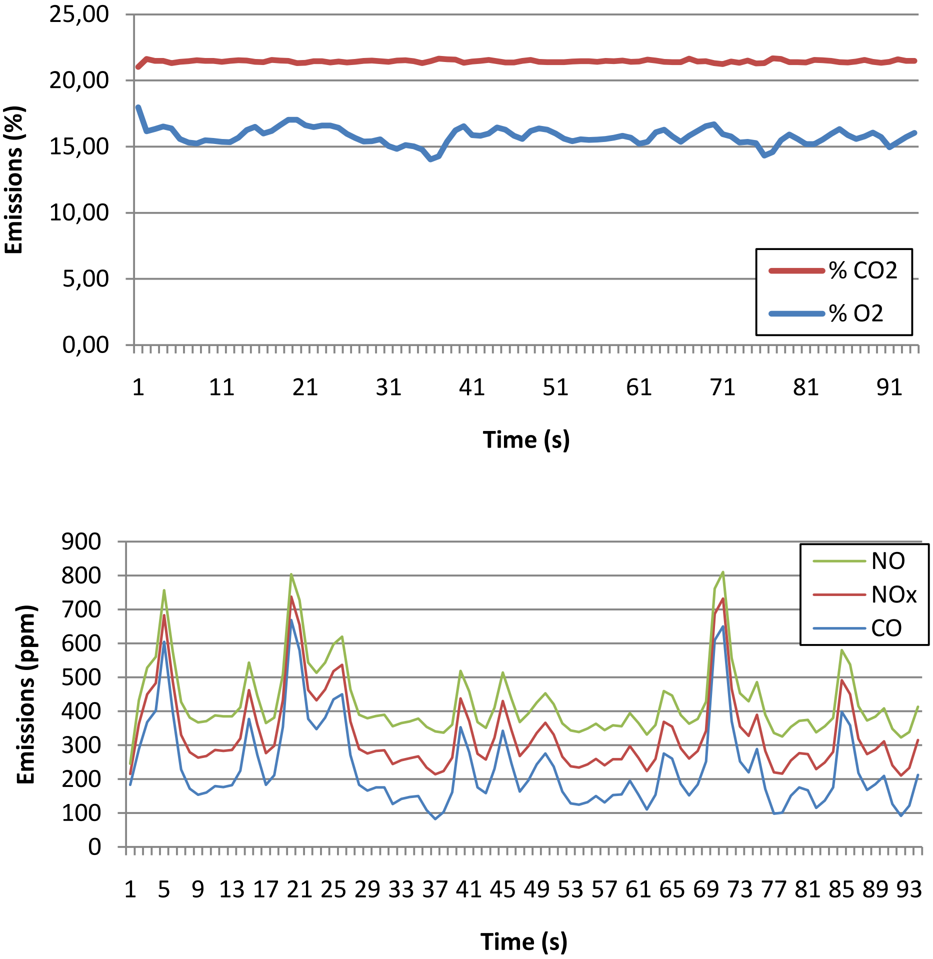
b)

Image A.4. 14: a) Trend of O_2 and CO_2 emissions during the combustion of pine pellets (10% RDF-test_10);b) Trend of CO, NO_x and NO emissions during the combustion of pine pellets (10% RDFs-test_10).



a) b)

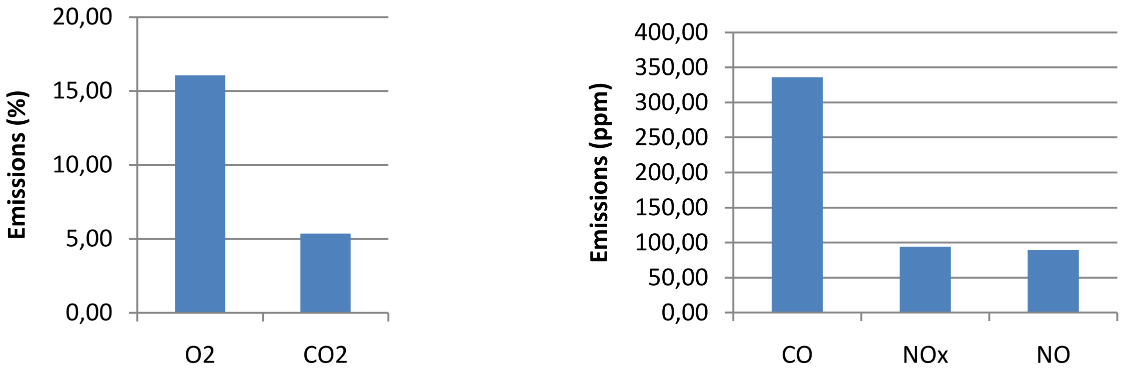
Image A.4. 15: a) Concentration of O_2 and CO_2 during the combustion of pine pellets (10%RDF test_12);b) Concentration of CO, NO_x and NO during the combustion of pine pellets (10% RDFs -test_12).



a)

b)

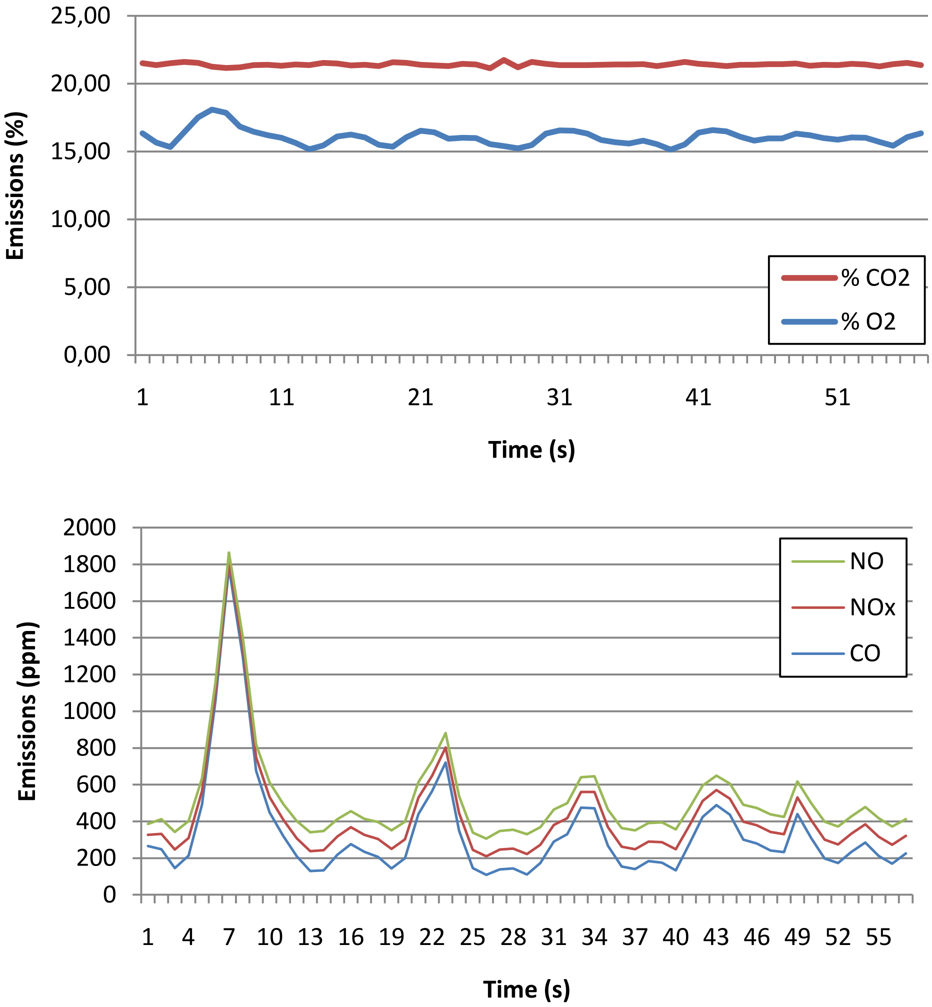
Image A.4. 16: a) Trend of O_2 and CO_2 emissions during the combustion of pine pellets (10% RDF-test_12);b) Trend of CO, NO_x and NO emissions during the combustion of pine pellets (10% RDF-test_12).



a)

b)

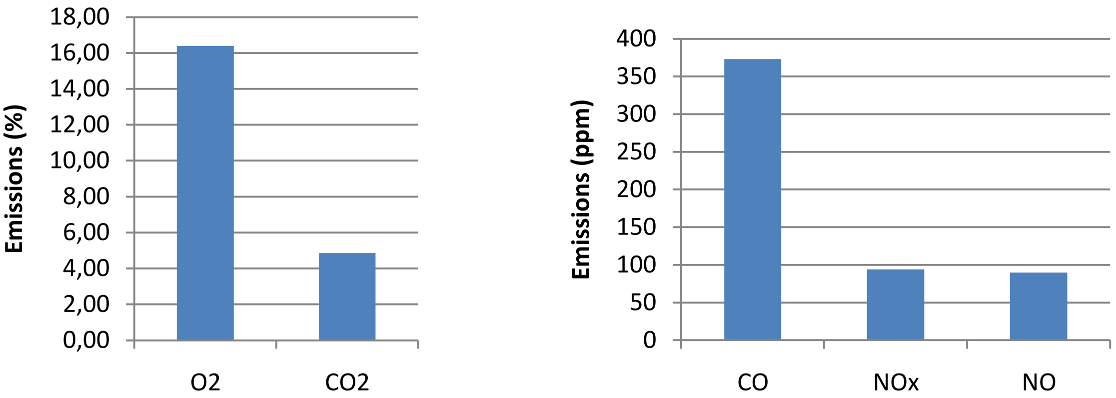
Image A.4. 17: a) Concentration of O_2 and CO_2 during the combustion of pine pellets (10%RDF test_14);b) Concentration of CO, NO_x and NO during the combustion of pine pellets (10% RDFs -test_14).



a)

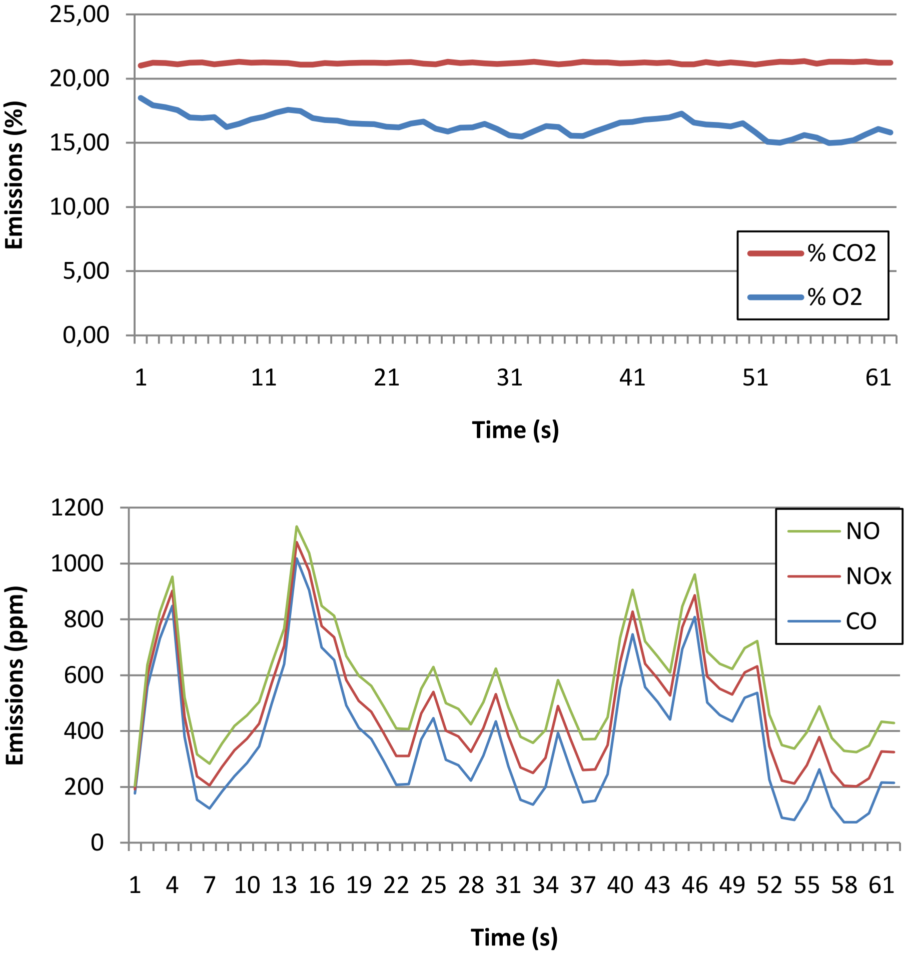
b)

Image A.4. 18: a) Trend of O_2 and CO_2 emissions during the combustion of pine pellets (10% RDF-test_14);b) Trend of CO, NO_x and NO emissions during the combustion of pine pellets (10% RDFs-test_14).



a) b)

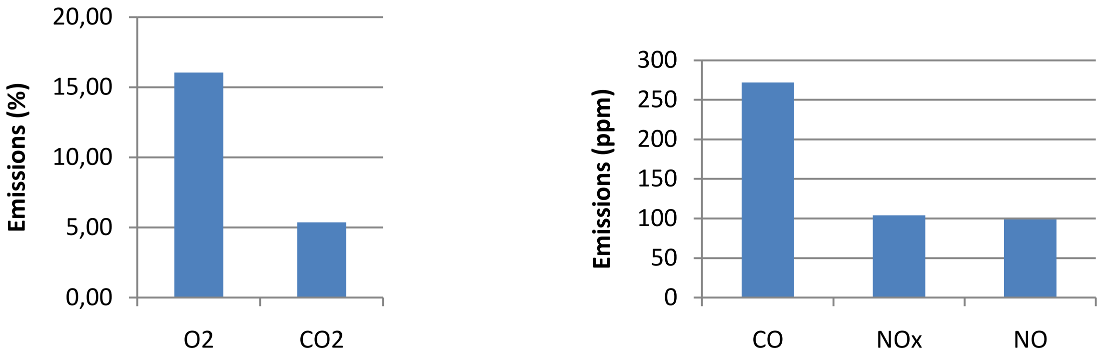
Image A.4. 19: a) Concentration of O_2 and CO_2 during the combustion of pine pellets (15%RDF test_13);b) Concentration of CO, NO_x and NO during the combustion of pine pellets (15% RDFs -test_13).



a)

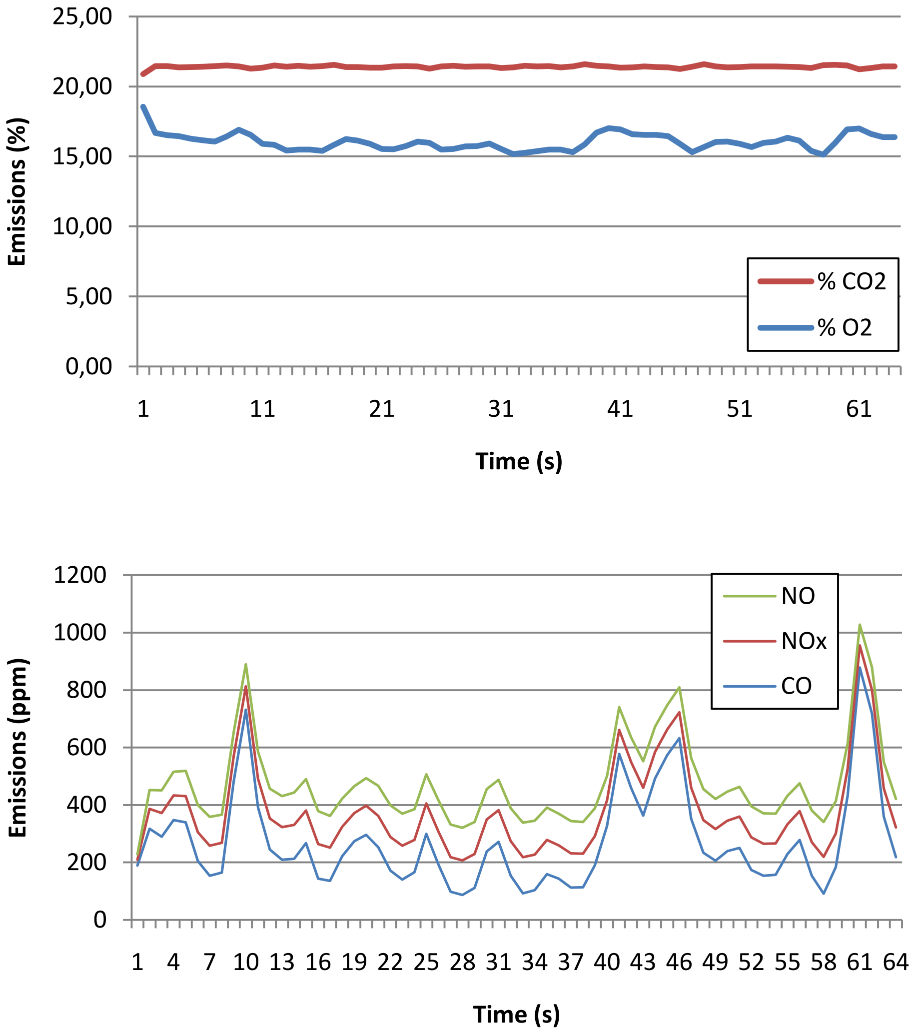
b)

Image A.4. 20: a) Trend of O_2 and CO_2 emissions during the combustion of pine pellets (15% RDF-test_13);b) Trend of CO, NO_x and NO emissions during the combustion of pine pellets (15% RDFs-test_13).



a) b)

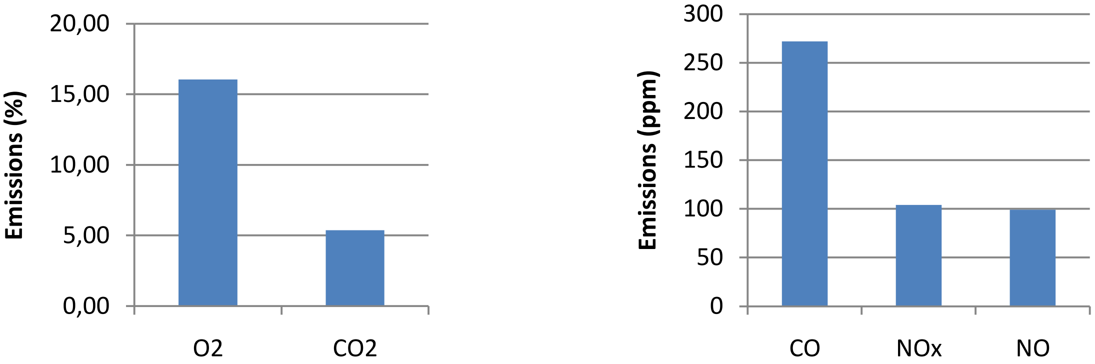
Image A.4. 21: a) Concentration of O_2 and CO_2 during the combustion of pine pellets (15%RDF test_15);b) Concentration of CO, NO_x and NO during the combustion of pine pellets (15% RDFs -test_15).



a)

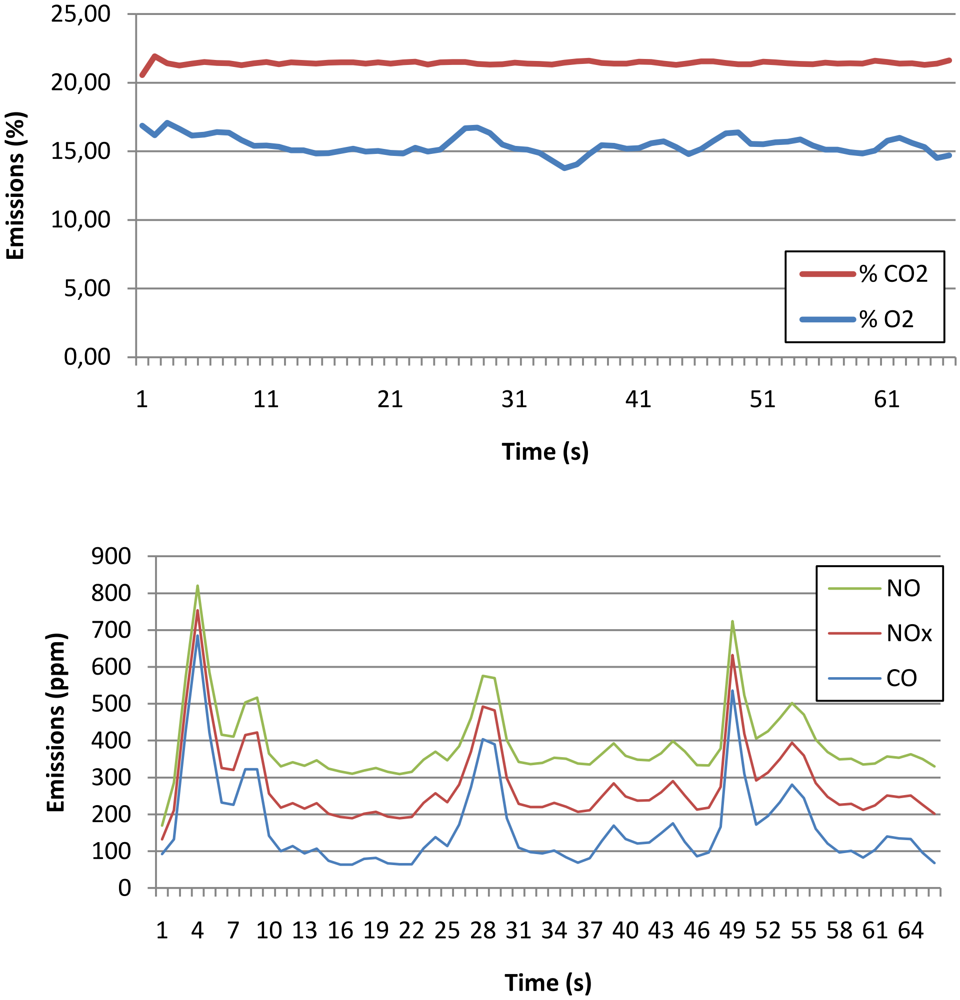
b)

Image A.4. 22: a) Trend of O_2 and CO_2 emissions during the combustion of pine pellets (15% RDF-test_15);b) Trend of CO, NO_x and NO emissions during the combustion of pine pellets (15% RDFs-test_15).



a) b)

Image A.4. 23: a) Concentration of O_2 and CO_2 during the combustion of pine pellets (15%RDF test_16);b) Concentration of CO, NO_x and NO during the combustion of pine pellets (15% RDFs -test_16).



a)

b)

Image A.4. 24: a) Trend of O_2 and CO_2 emissions during the combustion of pine pellets (15% RDF-test_16);b) Trend of CO, NO_x and NO emissions during the combustion of pine pellets (15% RDFs-test_16).

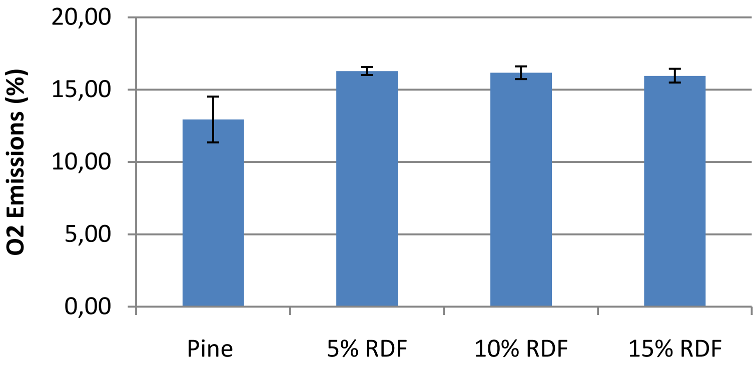


Image A.4. 25: Average O_2 of tests for the four types of pellets.

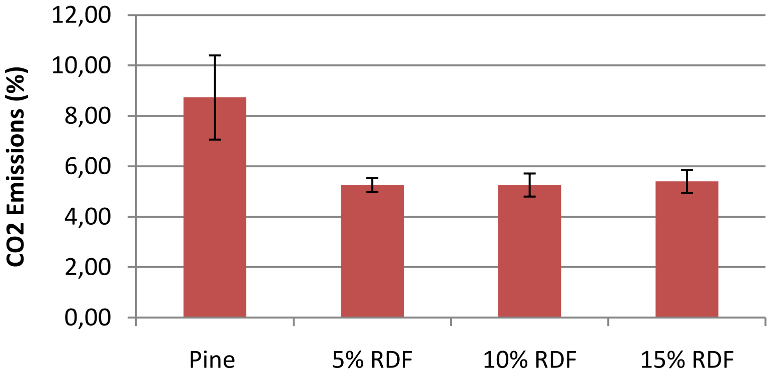


Image A.4. 26: Average CO_2 emissions from the combustion of the four types of pellets.

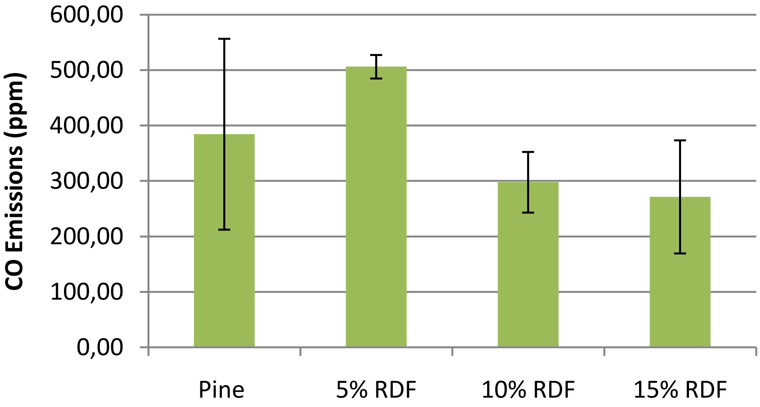


Image A.4. 27: Average CO emissions of the combustion of the four types of pellets.

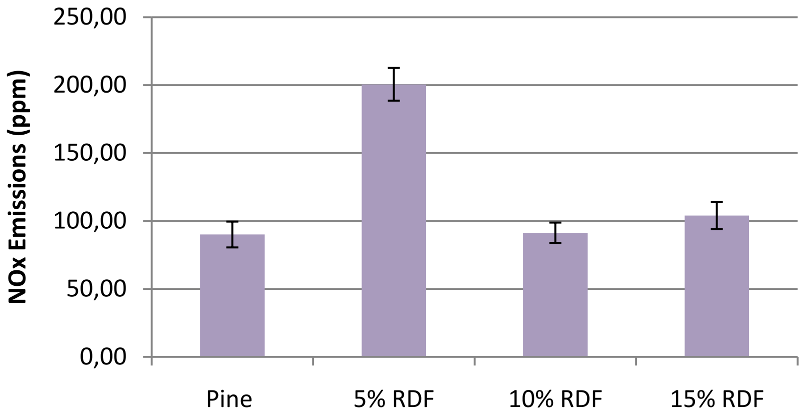


Image A.4. 28: Average NO_x emissions from the combustion of the four types of pellets.

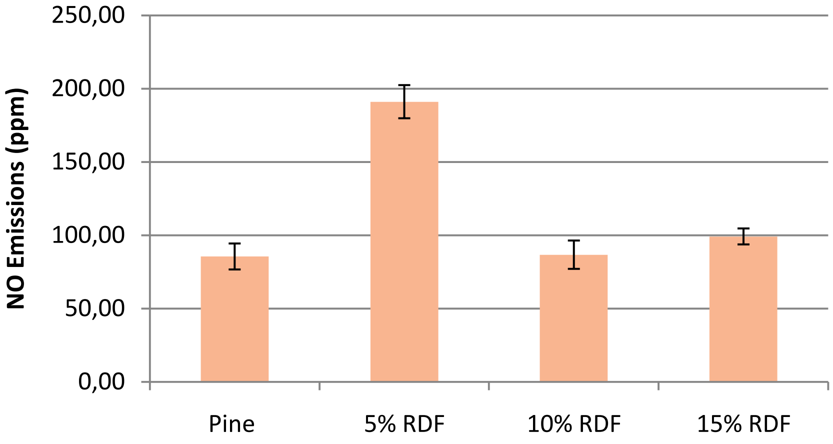


Image A.4. 29: Average NO emissions of combustion of the four types of pellets.